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Effects of Connected Autonomous Trucks on Highway Infrastructure Performance: A Whole-life Costing Approach to Design Optimisation

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Abstract

Faculty of Engineering and Physical Sciences

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Doctor of Philosophy

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Connected autonomous trucks (CATs) offer the prospect of vehicles executing highly defined, repeatable trajectories. This affects lane widths and pavement requirements, which must be assessed jointly as they are interlinked. Applying current design standards could lead to suboptimal designs because of conservatism. An optimised highway design model is required to ensure that autonomous vehicles are not detrimental to the network.

This study investigated the costs and benefits associated with innovative non-standard road cross-section remodelling options to accommodate CAT. Fifty cross-sections were generated, operating under 11 CAT ratios, resulting in 550 unique scenarios.

Over a 20-year design, this study used pricing models and unit prices to determine initial conversion and maintenance costs. TxME autonomous vehicles pavement analysis software was used to calculate the pavement failure frequency for CAT. Specially developed regression models were applied to calculate the same pavement behaviour parameters for manual trucks.

Accident, carbon dioxide emissions (CO_2e), and fuel consumption rates for manual vehicles were derived from historical data compiled by the UK government. CAT rates were calculated by analysing the results of the secondary studies from simulation modelling research. The overall travel times were determined from a complex amalgamation of inter-related mathematical formulae involving CAT proportions, theoretical free-flow speeds, actual speeds, effective speeds, posted speed limits, lane widths, traffic volumes, lane capacities, lane utilisation distributions, construction (conversion) cost-time models, and pavement failure rates.

The optimal highway design for low to mid-range MPR values was non-standard four-lane cross-section with 2.85m CAT lane, 3m manual truck lane, and two 2.575m passenger car lanes. At higher MPR values the optimal design is a standard three lane section of widths 3.65m, 3.70m and 3.65m. Demand-based sensitivity analysis of a further 275 scenarios found low CAT rates are detrimental to performance metrics, i.e., where daily vehicular flows are under 170,000. Beyond this demand, net benefits rise exponentially.

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Research Thesis: Declaration of Authorship

I, Hameed Jehanfo, declare that this thesis entitled '*Effects of Connected Autonomous Vehicles on Highway Infrastructure Performance: A Whole-life Costing Approach to Design Optimisation'*, and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University.
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
3. Where I have consulted the published work of others, this is always clearly attributed.
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
5. I have acknowledged all main sources of help.
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
7. Parts of this work have been published as: Jehanfo, Hameed et al. 20XX. For list of published articles see this section: '**Scientific Contributions and Publications from PhD Research**'.

Signed:

Hameed Jehanfo

02/05/2025

Scientific Contributions and Publications from PhD Research

Title	Year	Author(s)	Name of newspaper, book, etc.	Medium
Investigating whole-life cost savings of bespoke highway designs for Connected Autonomous Vehicles operating under platoon conditions	2019	Jehanfo, Hameed, Kaparias, Ioannis, Preston, Jonathan and Stevens, Alan	51st Annual Conference of the Universities' Transport Study Group, United Kingdom. 08 - 10 Jul 2019	Oral presentation
C/AVs could mean cheaper roads	2019	Jehanfo, Hameed	ITS International Magazine. October 2019.	Magazine article
Analyzing the Costs of Redesigning Highway Infrastructure Systems for Connected Autonomous Trucks	2022	Jehanfo, Hameed, Hu, Sheng, Kaparias, Ioannis, Preston, Jonathan, Foujie, Zhou, and Stevens, Alan	101st Transporation Research Board Annual Meeting, Washington DC, USA. 9-13 January 2022	Poster presentation
Redesigning highway infrastructure systems for Connected Autonomous Trucks	2022	Jehanfo, Hameed, Hu, Sheng, Kaparias, Ioannis, Preston, Jonathan, Foujie, Zhou, and Stevens, Alan	Journal of Transportation Engineering, Part A: Systems. DOI 10.1061/JTEPBS.0000762	Journal paper
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Revolutionising Road Resilience: The Game-Changing Impact of Self-Driving Cars on Combatting Climate Change	2023	Jehanfo, Hameed	RENKEI Research Fellowship Winter School: Climate Adaptation: Managing Future risks and building resilience in urban areas	Poster/oral presentation
Analyzing the Impact of Traffic Volumes on Key Performance Metrics for Connected Autonomous Truck-Enabled Highways	2023	Jehanfo, Hameed, Kaparias, Ioannis, Preston, Jonathan	8th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) 2023	Oral presentation and IEEE journal publication

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Definitions and Abbreviations

AADT................. ....Annual Average Daily Traffic - a measure of traffic volume calculated by dividing the total traffic volume of a road segment by the number of days in a year.

AASHTO................. ....American Association of State Highway and Transportation Officials - a non-profit, nonpartisan association representing highway and transportation departments in the United States.

AC...................................Asphalt Concrete - a type of pavement material consisting of asphalt binder and mineral aggregate.

ACC................. ....Adaptive Cruise Control - a feature integrated into autonomous vehicles that automatically adjusts the vehicle's speed to maintain a safe distance from the vehicle ahead. ACC utilizes sensors, such as radar or lidar, to detect surrounding vehicles and continuously monitors their speed and distance.

AV................. ....Autonomous Vehicles - vehicles equipped with advanced technologies allowing them to operate without human intervention.

BTC................. ....Bromilow Time-Cost - a construction pricing method estimating project cost and duration based on a direct proportion to project duration.

CACC................. ....Cooperative Adaptive Cruise Control - a system enabling vehicles to cooperate in maintaining safe following distances.

CARMA.............................Cloud-Assisted Real-time Methods for Autonomy - methods utilizing cloud computing for real-time autonomous vehicle operations.

CAT................. ....Connected Autonomous Truck - commercial truck equipped with autonomous driving technology.

CAV................................Connected and Automated Vehicles - vehicles with technologies enabling interaction with other vehicles and infrastructure.

CCAV............................ Centre for Connected and Autonomous Vehicles - a UK organization focusing on research and development in connected and autonomous vehicles.

CFFM............................ Collision-Free car Following Model - a model ensuring safe following distances between vehicles.

CTHP............................ Constant Time Headway Policy - a policy maintaining consistent time gaps between vehicles for safety.

CV................................ Connected Vehicle - a vehicle equipped with technology enabling communication with other vehicles and infrastructure.

DSRC............................ Dedicated Short-Range Communication - a technology enabling communication between vehicles and infrastructure.

EPSRC.......................... Engineering and Physical Sciences Research Council - a UK funding agency supporting research in engineering and physical sciences.

FEA/FEM....................... Finite Element Analysis/Method - numerical methods for analyzing structures and systems.

GDP.............................. Gross Domestic Product - the total value of goods and services produced within a country's borders in a specific period.

GHG............................. Greenhouse Gas - gases contributing to the greenhouse effect, such as carbon dioxide and methane.

GPS.............................. Global Positioning System - a satellite-based navigation system providing location and time information.

IMU.............................. Inertial Measurement Unit - a sensor measuring acceleration and rotation of a vehicle.

IoT................................ Internet of Things - a network of interconnected devices enabling data exchange and automation.

IoV............................... Internet of Vehicles - a concept integrating vehicles into the Internet of Things ecosystem.

ITS................................ Intelligent Transport System - technologies improving transportation efficiency, safety, and sustainability.

IVC................. ....Inter-Vehicular Communication - communication between vehicles for coordination and safety.

LIDAR................. ....Light Detection and Ranging - a remote sensing method using laser light to measure distances.

MMHW............................Method of Measurement for Highways Works - guidelines for measuring and maintaining highways.

MOVES................. ....Motor Vehicle Emission Simulator - a model estimating vehicle emissions and their impact.

NCAT................. ....National Center for Asphalt Technology - a research center focusing on asphalt materials and pavements.

NCHRP................. ....National Cooperative Highway Research Program - a US research program focusing on highway transportation.

NH................. ....National Highways - a UK government-owned company responsible for operating, maintaining, and improving the strategic road network in England.

OBU................. ....On-Board Unit - a device installed in vehicles for communication and data processing.

OPEX................. ....Operating Expenditure - ongoing expenses related to the operation of a transportation asset.

PCU................. .... Passenger Car Unit - a measure of traffic flow, representing the equivalent flow of passenger cars.

PSV................. ....Public Service Vehicle - a vehicle used for public transportation, such as buses and taxis.

ReCAP................. ....Research for Community Access Partnership - research initiative focusing on community access and transportation.

RSU................. ....Roadside Unit - a device installed along roadsides for communication with vehicles.

SAE.................................. Society of Automotive Engineers - a professional organization for automotive engineers.

SMMT................. .... Society of Motor Manufacturers and Traders - a UK based trade association representing the automotive industry.

SRN................. .... Strategic Road Network - a designated network of major roads and highways, typically consisting of arterial routes important for economic, social, and strategic reasons.

SSD................................. Stopping Sight Distance - the distance required for a driver to bring a vehicle to a complete stop safely, considering perception-reaction time and vehicle deceleration capability. It is a critical parameter used in highway design and traffic engineering to ensure adequate visibility and safety for drivers.

TM................................. Traffic Management - the planning and coordination of traffic flow, including the use of technology, infrastructure, and personnel to improve safety and efficiency.

TRB................. .... Transportation Research Board - a US organization focusing on transportation research and policy.

TRL................. .... Transport Research Laboratory - a research organization in the UK that specializes in transportation-related research and development.

TRRL............................. Transport and Road Research Laboratory - the former name of the Transport Research Laboratory, which was established in the UK in 1933.

TTI.................................. Texas Transportation Institute - a research institute focusing on transportation issues in Texas.

TTM................................ Temporary Traffic Management - the planning and coordination of traffic flow in construction zones and other temporary situations.

TxME.............................. Texas Mechanistic-Empirical Pavement Design and Analysis Program - a software tool developed for designing and evaluating pavement structures based on mechanistic-empirical principles. It integrates various factors such as materials properties, environmental conditions, and traffic loads to provide optimized pavement designs that enhance performance and durability while minimizing life-cycle costs. TxME allows transportation engineers and planners to make informed decisions regarding pavement design, maintenance, and rehabilitation strategies to ensure the longevity and sustainability.

V2I................................. Vehicle-to-Infrastructure - communication between vehicles and infrastructure for traffic management.

V2V................. .... Vehicle-to-Vehicle - communication between vehicles for coordination and safety.

V2X................. .... Vehicle-to-Everything - communication between vehicles and various elements of the transportation system.

VANET.......................... Vehicular Ad-Hoc Network - a network enabling communication between vehicles.

VISSIM.......................... Virtual Simulation and Modeling - a microscopic traffic simulation software used for modeling and analyzing transportation systems.

VIVUS................. .... Virtual Intelligent Vehicle Urban Simulator - a simulation tool for testing and evaluating intelligent vehicle systems.

VMT................. .... Vehicle Miles Travelled - a measure of total vehicle travel over a specific period.

WebTAG......................... Web-based Transport Analysis Guidance - a set of guidelines and tools developed by the UK Department for Transport to support the appraisal and evaluation of transport projects, providing a framework for assessing the costs, benefits, and wider impacts of different transport interventions, including economic analysis, environmental assessment, and social and distributional impacts.

WLC................. .... Whole Life Cost - the total cost of owning and operating a transportation asset over its entire life cycle, including initial costs, maintenance, and disposal.

Chapter 1 INTRODUCTION

1.1 Background

1.1.1 The drive towards automation

Globally, the last two decades have seen a significant, steady increase in the resources invested into the development of connected autonomous vehicles (CAVs). In various countries, particularly in advanced economies, entities including governments, private businesses (such as vehicle manufacturers and software technologies developers) and institutions are conducting various research work focussed on self-driving vehicle technology. Based on this, a 2015 study estimated that by 2025, the global intelligent mobility market could be worth £900bn per year, with fully autonomous vehicles predicted to hold a 25% market share in the automobile industry by 2030 (Leech et al., 2015). A much more recent research conducted by Raposo et al. (2022) reiterated the global forecast figures by Leech et al, but also provided a longer term, Eurocentric analysis which found that the continents automotive industry will be worth an extra EUR570bn a year by 2050 due to connected and autonomous mobility market effects (Raposo et al., 2022).

The UK has not been immune to the world-wide excitement generated by the prospects of self-driving vehicles and has demonstrated real ambition to play a pioneering role in bringing this revolutionary transport system to reality. A significant moment came when, in the 2015 Spring Budget Statement, the then Chancellor of the Exchequer, the Rt Hon George Osborne MP, announced £100 million worth of investments for research into CAVs. This amount was to be match-funded by industry. Four months later, the Centre for Connected and Autonomous Vehicles (CCAV) was inaugurated with the sole objective to "keep the UK at the forefront of the development and deployment of [CAV] technology" (Hopkins and Schwanen, 2018). Over a period of 5 years (2014 to 2018 inclusive), government and industry invested a combined £250m into more than 70 projects, involving 200 partner organisations (Centre for Connected and Automated Vehicles, 2018).

The UK government further entrenched its resolve to implement CAVs imminently by announcing in the 2017 Autumn Budget that radical legislative changes would be made to permit fully autonomous vehicle on public roads as soon as 2021. This led directly to enactment of the Automated and Electric Vehicles Act 2018, which provides insurance cover for automated vehicles involved in collisions (Channon, 2019). This legislation was a significant breakthrough, because much of the anticipated reluctance and apprehension to self-driving vehicles relates to liabilities in accidents.

Notwithstanding the UK's ambitions, a House of Commons Briefing Paper recognised that the existing UK road network is unfit for CAVs implementation (Clarke and Butcher, 2017). This finding is to be expected given that all the roads were designed and constructed using standards that correspond to conventionally driven vehicles. Any decision to apply the current standards or develop a new approach to road design for CAVs must be supported by adequately researched evidence, or risk leading to over-designed highways that over-compensates for perceived problems with CAVs or under-designed highways that causes infrastructure failure.

1.1.2 Public anxiety to new technology

Although advantages such as improved safety, fuel economy, independence and convenience are regularly emphasised as clear benefits of CAVs, there are those who advance concerns about handing responsibility for a complex, nuanced driving task to a machine.

A particular criticism of autonomous cars is that the sensors and image processors are unable to make the subtle distinctions between hazards, and that this ability is the preserve of the complex human brain intuition. Such views gained more support in the wake of the March 2018 Tesla self-driving vehicle accident in Tempe, Arizona, in which Elaine Herzberg was fatally injured. The accident led to the general public expressing serious concerns over the safety of a vehicle that is not controlled by a human.

Even with these scepticisms, the accident rate per distance travelled of these trial autonomous vehicles are still much lower than those of their manually driven vehicles counterparts. Once implemented, it is estimated that CAVs will prevent more than 150 road deaths per year in the UK (Society of Motor Manufacturers and Traders, 2017). The hazard detection and avoidance systems are constantly being refined, further increasing the likelihood of deployment and public acceptance.

1.2 Managing risks to the highway network

1.2.1 The economic importance of roads

The UK economy relies heavily on a properly functional highway network, as over 90% of goods are transported by road (MDS Transmodal, 2019). The UK Strategic Road Network (SRN) plays an important role in the economic and social aspects of the nation. The services sector alone - of which freight transportation is a significant component - accounts for 80% of the UK's GDP. Also, the construction sector, which encompasses road construction and maintenance makes up 6% of the UK national Gross Domestic Product (GDP) (House of Commons Library, 2020). Road freight enjoys a clear dominance in the freight transport derived demand space because of its flexibility, cost-effectiveness, absence of complicated regulations, and good connectivity. Figure 1-1 underlines the clear prominence of roads to the UK economy, compared to other major transport modes, (Government Office for Science, 2019). Due to this invaluable contribution of roads, relatively minor impacts on highway infrastructure can have substantial economic implications.

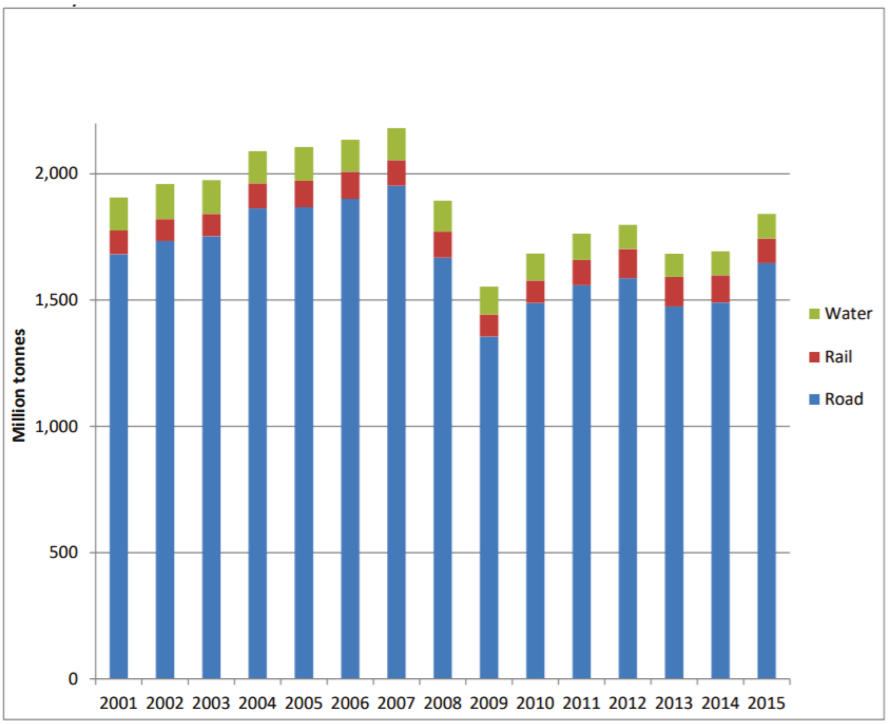


Figure 1-1 Freight transport by mode. From the Government Office for Science (2019)

Financial figures associated with the road network contextualises its place in the economy. As at 2020, the existing national road infrastructure was valued at £100 billion, with government committing to expend a further £27.4 billion over a five-year period to build new road corridors and upgrade existing ones (Department for Transport, 2020a).

These expensive and vital national infrastructure need to be looked after and protected. But the way these assets were previously designed, and their maintenance regime modelled, will change due to the introduction of connected autonomous vehicles. Conventional design and assessment methods based exclusively on manual vehicles (MVs) for these high-value road assets may now not be economically or technically appropriate, as partially autonomous vehicles are already common on public roads. Throughout the 2010s, there has been increasing confidence that fully autonomous vehicles will become part of mainstream road transport in the near future (Leech et al., 2015), and the end of that decade witnessed well-supported forecasts about the imminence of completely driverless vehicles (Hummer, 2020).

The generally held view within the connected and autonomous vehicle (CAV) sector is that the lane distributional certainty, reduced reaction times and increased control offered by self-driving technology will improve the key measures of transportation performance, namely safety, greenhouse gas emissions, and traffic flows. However, this perspective is not totally undisputed. Particularly, on the point of traffic flow, specific studies have shown that this could worsen under CAVs as a result of their disruptive effects, risk aversion and increased headways to over-compensate for the novelty of the technologies (Michael et al., 1998). This is crucial because traffic volume is one of the main factors that determines the suitability of engineering proposals, as the efficiency of traffic interventions is highly sensitive to volume of traffic. Interchange or junction types, lane widths, and number of lanes are all design decisions based on traffic levels. The use of Intelligent Transport Systems (ITS) and more broadly, technologies in transport, are also heavily influenced by traffic demands. For instance, the deployment of the Smart Motorways concept and choice of signal control systems, are, at least, partly determined by capacity requirements.

1.2.2 Disruption to highway engineering

Highway design standards used today are still based on traffic consisting of an entirely manually driven vehicle fleet, where drivers are required to perform all driving tasks (Level 0 Automation). The continued use of these design standards is in spite of the prevalence of several driver-assist technologies including collision avoidance, lane departure warning, vehicle centring, adaptive cruise control and vehicle stabilisation (Levels 1-3). This trend of diminishing reliance on a human driver is predicted to continue until fully automated Level 5 vehicles are found on our roads (Leech et al., 2015).

The traditional highway engineering approaches have not adapted to the latest vehicle technologies. Even the recent restructuring and revisions to the UK Design Manual for Roads and Bridges (DMRB) since March 2020 has not resulted in the modification of highway parameters to account for CAVs or connected autonomous trucks (CATs). In the US, the latest edition of the Highway Capacity Manual (HCM7) released in 2022 incorporates methods to determine capacity impacts of CAVs through the development of capacity adjustment factors based on MPRs and AADT values (Transportation Research Board (Washington District of Columbia), 2022). Therefore, it is important that the UK at least keeps pace and similarly upgrade technical design guidance.

Extensive research and development work is being undertaken towards full driving autonomy. The nature of CAVs technologies, including detection of hazards, vehicle lateral and longitudinal control, and other human influences provides evidence on how their operation will change fundamental highway design parameters. Specifically, the object-detecting sensors in CAVs are unlike the biological eye in image interpretation and processing, and roadside infrastructure designs also rely on the effect of object positions on driver psychology.

Moreover, the desirable minimum setback distances for structural supports and safety barriers are based on how motorists react to objects placed close to the running carriageway (Department of Transport, 2007). Stopping sight distances and lane widths will also be impacted by CAVs by the perception, localisation and planning systems of CAVs. Therefore, there is a need to review human-dependent design aspects of road engineering and investigate how they could be affected by the introduction of CAVs.

According to a World Road Association study of international design practices, 60% of all the known driver physiological, sensori-motor and cognitive patterns that can influence vehicle handling have been accounted for in highway engineering standards (Birth et al., 2011).

The importance of driver psychology in current road design standards is further highlighted in research work published in TRL Report 564, which found that the main carriageway design parameters in highway engineering are linked to driver cognitive loads and risk perceptions (Elliott et al., 2003).

A TRL study published as TRL Report 332 (Maycock et al., 1998), visibility, braking distances and overtaking opportunities in standards to which designs must comply are also directly derived from driver perception-reaction times. These reaction times are calculated using models that involve complex stages of human and vehicle response elements.

Further research has also asserted that the fundamental facets of junction layout design rely on the psycho-physical state of drivers to analyse functional and capacity performance of junctions (Brown, 1995).

A consequence of integrating human physiological factors into highway design philosophies is that conventional engineering parameters are conservative, as appropriate margins of safety are built into proposals to account for non-deterministic human behaviour. Specifically, very important design criteria such as lateral geometrics, braking and sight restrictions, are based on relatively conservative assumptions regarding the capabilities of drivers to perceive and react to stimuli (AASHTO, 2004). In the US, geometric parameters are derived with consideration for 'driver skill' (Stonex et al., 1941).

1.2.3 Reality and consequences of threats

To ensure that all the advertised benefits of CAVs are realised, while simultaneously addressing the potential drawbacks, road design engineers and transport professionals need to review how this imminent change in vehicle mix will impact on existing engineering design philosophies. This is especially crucial as roads have a very important socio-economic impact in countries the world over. Potential threats or even opportunities presented by the autonomous vehicle revolution deserve the attention of technical professionals in the highway sector.

Projections into the future of road transport show that over the next 30 years CAVs will radically affect the transport networks, owing to their technological demands and comparatively different driving regimes as compared to the more manual, legacy vehicles. This will result in a complete overhaul of road transport systems (Becker and Axhausen, 2017). Similar research have shown that, because transportation systems are highly complex, existing assessment tools are potentially inappropriate for the new CAVs driving regime (Makridis et al., 2018a). Consequently, novel approaches to designing and assessing road transportation systems, and predicting the impact of connectivity and autonomy, need to be formulated.

1.3 Engaging with national and international CAV study efforts

As CAVs are a novel transport concept, participation in specialist brainstorming events focussed on CAVs was required to understand experts' views on how highway designs might be affected by autonomous vehicles. Among these events, were the Meridian Workshop and the Emulsion Workshop. The Meridian workshop was organised by Zenzic to bring together multi-disciplinary cross section of experts to help understand the challenges to CAVs implementation. The format of the workshop was to form groups of 5 individuals plus a facilitator, each with a unique perspective – see Figure 1-2. The workshops were held over several days in the spring of 2019 in London. Participation in the Meridian workshops was strictly by direct invitation by the organisers. The workshop culminated in the production of an interactive UK Roadmap for CAVs implementation (Zenzic, 2019).

Figure 1-2 Making contributions at Meridian brainstorming workshop

The Emulsion workshops were conducted to gain insights into different members of society and how CAVs would affect their lives (Lyons, 2020). Participation was through an online application, which was then vetted by the organisers, Landor. Participants at the Emulsion workshops deliberated on the preparedness of current physical and policy systems for CAVs (see Figure 1-3 and Figure 1-4).

Figure 1-3 Attendance at Emulsion workshop in Birmingham. From Lyons (2020).

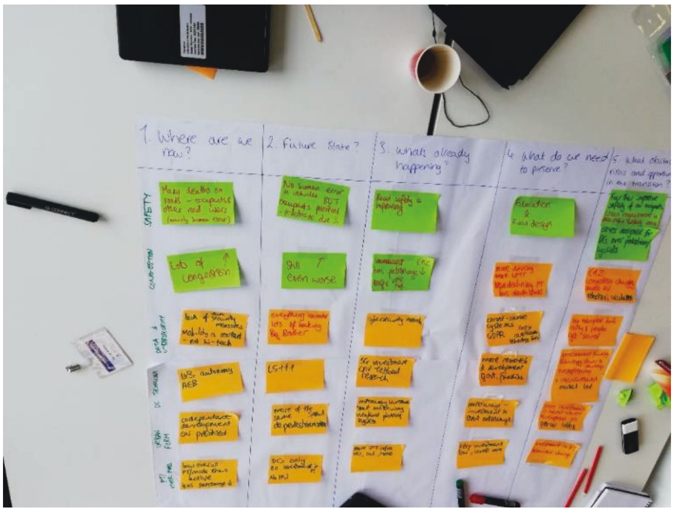


Figure 1-4 Emulsion workshop montage on pros and cons of CAVs

Finally, the author organised and moderated discussions with the Sustainable Transport Unit at European Commission Joint Research Centre based in Italy. During these discussions, details of test sites - such as the Navya Shuttles in Lyon, France and Sion, Switzerland - came to light. This helped explain some of the vehicle lateral control capabilities, which were applied in designing feasible cross-section alternatives for the study.

Participation in these specialist events broadened and deepened knowledge is this area and provided high-level appreciation of challenges and opportunities from CAVs.

It would appear, therefore, that the CAV-related investment, research, development activity and legislative changes in the UK overshadow any misgivings held by sceptics towards the introduction of CAVs. Hence, the expectation that driverless vehicles will imminently become part of mainstream road travel is sufficiently justified.

1.4 Research motivation

1.4.1 Analytical complexities of designing for CATs

Autonomous vehicles are expected to share the same, existing roads with MVs (Hummer, 2020), and one option for incorporating CATs is to have wider lanes, so that CATs can spread their wheel load uniformly, thereby reducing maintenance frequency. However, this could increase initial conversion costs and/or reduce roadspace available for manual vehicles. Conversely, providing a narrow lane to take advantage of the close wheel tracking of CATs will release more roadspace that can be used by manual vehicles, with the expectation of improved traffic flows. But this will likely lead to premature pavement failure due to wheel load concentration from channelisation.

Furthermore, cross-sections also affect how temporary traffic management are configured during roadworks to either undertake initial conversion work, or during maintenance activities. These temporary roadworks attract substantial proportions of highway authorities' budgets, and also have inherent implications for road safety and capacity (Nassrullah and Yousif, 2019). It is imperative, therefore, that proposals for remodelling highways for CATs assess performance, not only in times of normal operations, but also during temporary traffic management (TTM) for roadworks (Bussey, 2019).

The combination of these different factors means deciphering the net benefits of designing for CATs requires complex analysis that takes in the various influencing factors.

1.4.2 Knowledge gap

There is currently no comprehensive model for analysing design options for CATs that considers all the various influencing factors in terms of benefits and cost. The study that comes closest to addressing this gap was conducted without considering the effect of different lane widths (Hoque et al., 2021). The study ignores the relationship between pavement performance and cross-sectional features. This means that decisions for selecting road design approach for CAT implementation risks being based on an inexhaustive, or incorrectly weighted, set of factors.

Hence, this research is required to produce a comprehensive model for analysing and comparing alternatives for design roads for CATs.

1.5 Study aim and objectives

This study sought to assess engineering alternatives for implementing a dedicated CAT lane, and then comparing operational performance during both normal and temporary traffic conditions, expressed in monetary value. This approach enabled the comparison of immediate, medium, and long-term effects of various cross-section alternatives.

1.5.1 Aim

The core aim of this research is to develop a method for enhancing highway design for CAT penetration. This will provide a framework or decision-supporting tool for modifying current highway design standards. The research focuses on trucks. Compared to private motorists, commercial vehicles are likely to experience substantial uptake in full CAV-enabled capabilities more imminently, as significant labour cost savings have been forecast for this vehicle category (Hummer, 2020). It is also easier to provide dedicated CAV infrastructure in trunk road environments, where over 90% of truck mileage occurs (Department for Transport, 2020b).

1.5.2 Objectives

The following objectives have been identified to achieve the overall research aim:

1. Conduct exploratory study into highway designs parameters that require modifications for CAVs. To be achieved by investigating the operational behaviours of CAVs and carrying out an assessment of how they differ from manual vehicles in the context of current highway engineering design principles, theories, and philosophies. It is expected that the elements of highway design that will be affected due to connected and autonomous vehicles technology will begin to emerge.

2. Develop methodologies for calculating new highway performance metrics for CAVs using new mathematical traffic and transport economic models for CAVs. These will be based on systematic research into existing models for legacy vehicles. Using secondary data from the portfolio of current research findings on the behaviour of CAVs, specific parameters will be modified. These parameters will include vehicle wheel wander and channalisations; vehicle lane choice and traffic volume distributions across lanes in multi-lane freeways; compliance with

speed limits; impacts of lane widths on flow speeds; safety; platooning of HGVs and its effects on lane capacity, travel time, fuel consumptions and emission.

3. Produce whole-life cost optimisation model for highway design for CAVs. This model should enable input of different design parameters so that whole-life costs can be measured.

4. Validate the performance of the optimised highway design model against a range of traffic flow conditions. While CAVs are generally predicted to provide improvements for the highways, there are also disbenefits associated with their implementation, not least due to their anticipated disruptive characteristics from being different and novel with respect to conventional vehicles. This decision support model will help determine where that balance lies between positive and negative impacts of CAVs.

1.6 Structure of Thesis

Chapter 1 Sets the scene for the research. Basic concepts and terminologies around connected autonomous vehicle technology are introduced, and explanations for why they present a problem for highway engineering is described. The motivation for the research is also explained, and the research aim, and objects are outlined.

Chapter 2 Contains a collection and synthesis of extensive information on how connected autonomous vehicles are predicted to operate, comparing differences in characteristics between connected autonomous vehicles and manual vehicles.

Chapter 3 Provides a detailed review of the current technical design standards for road geometric cross-sections engineering and pavement structural analysis. The underpinning theoretical principles that govern these standards are examined. In this chapter, the intrinsic connection between highway cross-section and pavement structural analysis is established.

Chapter 4 Presents a critical review of existing literature on how autonomous vehicles affect pavement performance and carriageway cross-sectional configuration. The limitations of these existing research emerge from this critical review, culminating in a statement on the knowledge gap, which this PhD seeks to address.

Chapter 5 Details the main research methods, and justifications of the assumptions used in this research to derive costs for road authorities. The approach to developing and analysing scenarios is also outlined. Results from this analysis are presented and discussed.

Chapter 6 Outlines the complex model amalgamations, simulations, application and interpretation of secondary data used to develop various whole-life cost components for this study. The focus of this chapter is on the costs incurred by road users.

Chapter 7 Summarises the findings of this research, reflects on practical uses of the work, provides an appraisal against the original aims and objects, and outlines opportunities for extending further on the research's contribution to knowledge or improving on the results.

The layout of the thesis is shown in Figure 1-5.

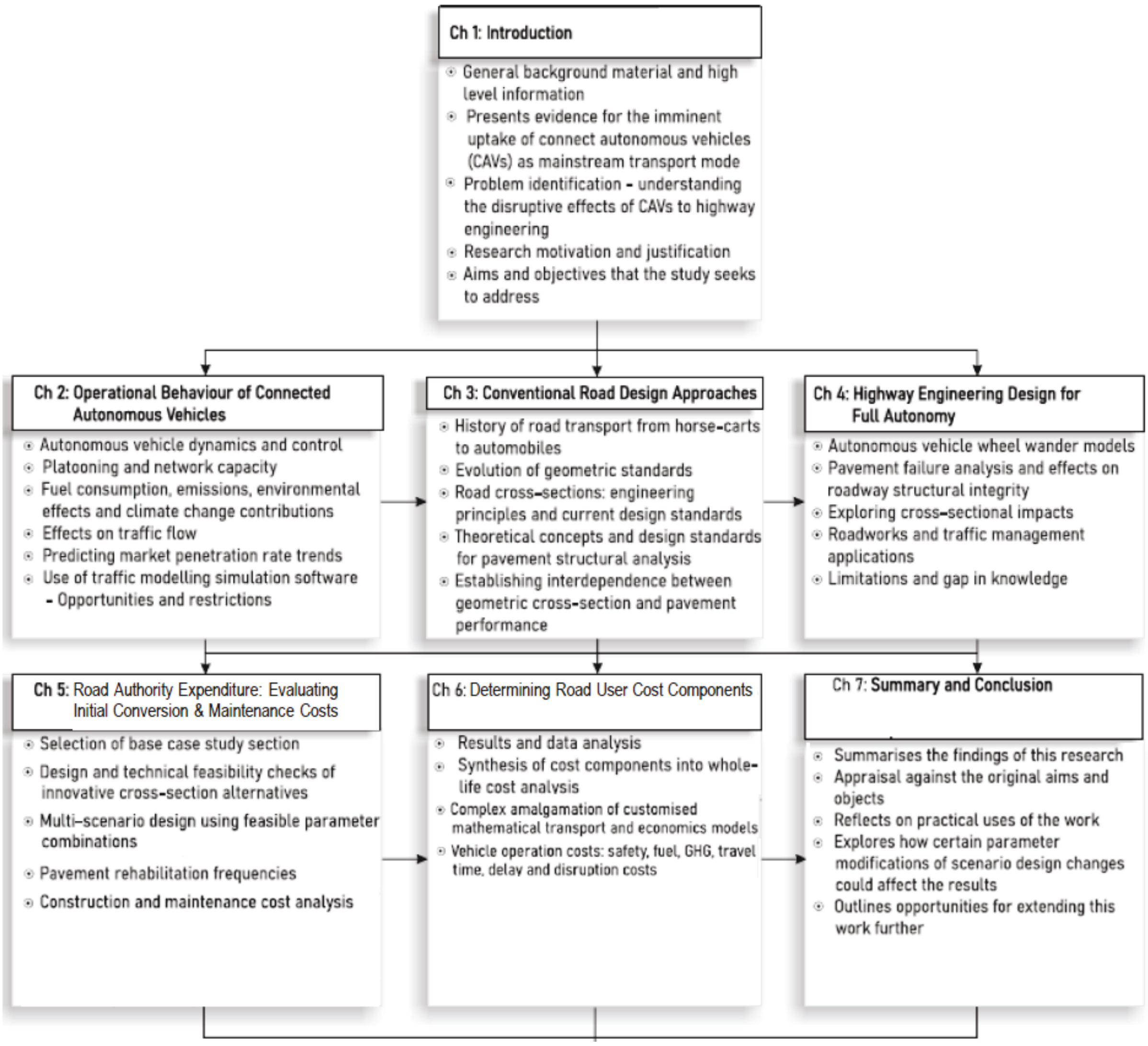


Figure 1-5 Depiction of the structure and layout of PhD thesis

Chapter 2 OPERATIONAL BEHAVIOUR OF CONNECTED AUTONOMOUS VEHICLES: ASSUMPTIONS AND SUPPORTING EVIDENCE

At the time of conducting this PhD research, CAVs have yet to be introduced onto mainstream highway networks, hence this precludes access to real data. Simulation and modelling research that predicts the behaviour and performance of CAVs, therefore, have been relied upon as secondary sources of information for this study. These studies relate to traffic flow parameters (speed, spacing, capacity and density), safety, and fuel consumption aspects.

2.1 Technical concepts and market trends

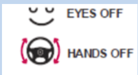
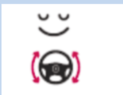
This section aims to find the fundamental operational differences between CAVs and manual vehicles by examining those extra technological and infrastructural requirements for CAVs, above and beyond what would normally be required for manual vehicles.

2.1.1 Technologies and terminologies

The successful operation of CAV driving mode will require complex and advanced hardware and software systems, which will be supported by both in-car and out-car infrastructure. A key point to note is that CAV systems consist of various technologies. Connected vehicle (CV) technologies generally support data transmittal between vehicles and other external receivers in the form of vehicle-to-vehicle (V2V), vehicle to infrastructure (V2I), or vehicle to everything (V2X) technologies. CV technology is already fitted by several car manufacturers in the form of dynamic route guidance provided by satellite navigation systems (Atkins, 2015).

On the other hand, Autonomous vehicle (AV) technologies are those specific systems that reduce human input into various driving tasks. Although there are various definitions, the most widely used classification system of AV technologies is the one developed by the Society of Automotive Engineers (SAE) (Litman, 2017). This uses six levels which correspond to the degree of driver effort and required input. The SAE's definitions are detailed in Table 2-1.

Table 2-1 Autonomy levels definitions. Adapted from Litman (2017)

LEVEL	NAME	DIAGRAM	NARRATIVE DEFINITION	STEERING AND SPEED CONTROL	MONITORING DRIVING SITUATION	FALLBACK DRIVING TASK	SYSTEM CAPABILITY
Human driver monitors the driving environment							
0	**No Automation**		the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems, such as Lane Departure Warnings and Automatic Transmission	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**		the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment (e.g., Cruise Control and Lane Keep Assist System) and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**		the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* performs all remaining aspects of the *dynamic driving task* *(eg Park Assist Systems, Autonomous Emergency Braking Systems, Basic Platooning)*	**System**	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment							
3	**Conditional Automation**		the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene* (e.g., Remote control parking, Motorway Assist, Mid-range platooning)	System	**System**	Human driver	Some driving modes
4	**High Automation**		the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene (e.g., Full motorway pilot, Advanced Platooning)*	System	System	**System**	Some driving modes
5	**Full Automation**		full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver* (Driverless)	System	System	System	**All driving modes**

2.1.2 Partial automation acceptance

Crucially, consumer behaviour indicates a growing willingness to purchase vehicles with these AV technologies. In 2015, over half of vehicles registered in the UK were at Level 2 Automation, according to the SMMT (Society of Motor Manufacturers and Traders, 2016). Table 2-2 details the breakdown of the specific types of driver assistance systems installed in these vehicles. The table shows that the single, most common technology feature was collision warning system, which was fitted in 58.1% of vehicles, either as standard or on request by buyers. In addition, blind spot monitoring was found to be the most frequently requested optional feature, which may indicate that motorists feel they require assistance to undertake parking manoeuvres.

To further demonstrate the upward trend of vehicle technology, data collected and analysed by the motor industry in 2018 showed that 70% of new vehicles available on the UK market have driver assistance systems (Society of Motor Manufacturers and Traders, 2018).

Table 2-2 New cars Driver Assistance Systems. By the SMMT (2018).

	Fitted as standard	**Optional fitment**	**Total**
Adaptive cruise control	147,476 **(5.6%)**	687,344 **(26.1%)**	834,820 (**31.7%)**
Autonomous emergency	474,030 **(18%)**	553,035 **(21%)**	1,027,066 **(39%)**
Blind spot monitoring	89,539 **(3.4%)**	853,255 **(32.4%)**	942,794 **(35.8%)**
Collision warning system	808,485 **(30.7%)**	721,579 **(27.4%)**	1,530,065 **(58.1%)**

Clearly, both the quantity and sophistication of CAVs technology is gaining increasing widespread penetration into mainstream road transport. The effect of this, therefore, needs to be thoroughly investigated from highway design perspective.

2.1.3 Composition of the Full autonomy (Level 5) system

The architectural technology that is expected to drive full autonomy in road vehicles is composed of five functional systems: Localisation, Perception, Planning, Control and System management.

Localisation involves the use of GPS-enabled devised to locate the vehicle (Kockelman, 2017).

Perception systems use mass data-based artificial intelligence with sensors evaluating driving environment, detecting hazards and interpreting road signs etc, such as shown in Figure 2-1 (Lee, 2018).

Figure 2-1 Image capture and classification. By Lee (2018).

Planning system processes highly complex data to determine travel paths and required manoeuvres, including cooperative adaptive cruise control (CACC)-operated truck platooning system (Chen and Park, 2019), using on-board units (OBUs) and Road Side Units (RSUs) to transmit information. See Figure 2-2 and Figure 2-3.

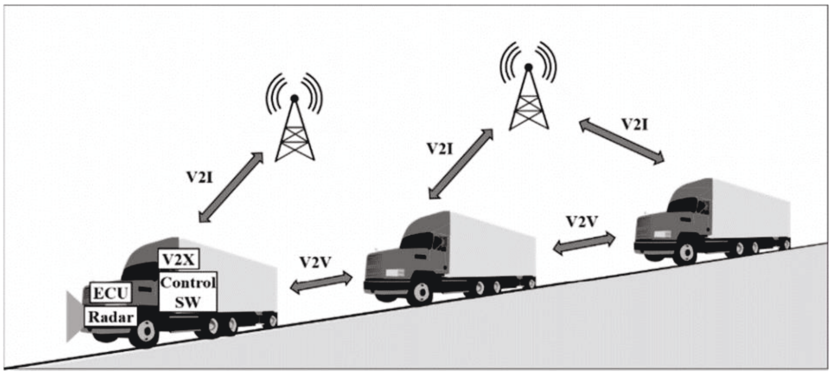


Figure 2-2 Concept of platooning. From Chen and Park (2019).

Figure 2-3 Roadside Unit. From Chen et al. (2018).

The Control functional system then manipulates the vehicle, using co-operative driving supported by V2V, V2I and V2C communications.

Systems management oversees all CAVs systems and human interface, using, for example, vehicular ad-hoc networks (VANETs) concepts to define inter vehicular communication (IVC) topologies., as illustrated in Figure 2-4 (Rakkesh et al., 2017).

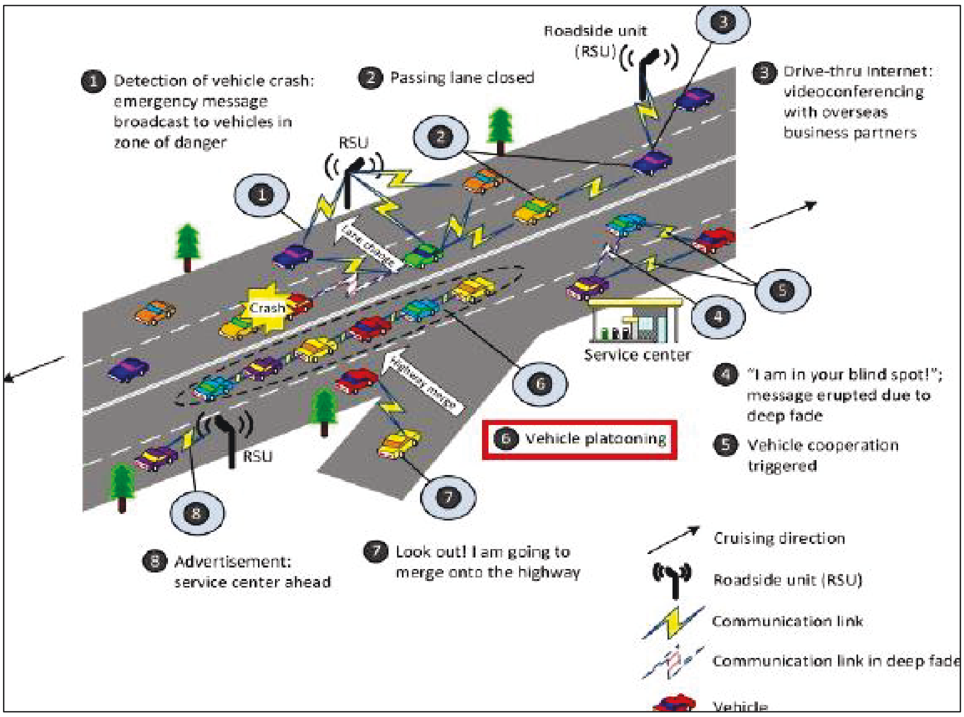


Figure 2-4 VANET Communication interfaces. Taken from Rakkesh et al. (2017)

2.1.4 Achieved and projected progress to full automation

It is clear from the foregoing that much progress has been made to develop and refine self-driving technologies.

For the locations and perception systems, methods incorporating 3-D LIDAR, Inertial Measurement Unit (IMU) and GPS systems have now been developed which could further improve the lateral tracking accuracy of autonomous vehicles, compared to the human driving versions, which underpin DMRB standards presently. Maximum lateral error of 10cm can already be achieved with these systems (Levinson et al., 2007). Nonetheless, it is expected that with further developments, this accuracy will improve. (Nazer et al., 2022). In addition, emergence of concepts such as Internet of Things (IoT) and Internet of Vehicles (IoV) should improve the economic, safety and accuracy performance of current localisation and perceptions systems, furthering the debate for introducing CAVs (Kuutti et al., 2018).

Regarding the planning systems technologies, CACC and platooning have been found to improve traffic flows, receiving very high commendations in trials (Harfouch et al., 2018, Shladover et al., 2018, Zegers et al., 2018). Furthermore, dedicated short-range communication (DSRC) with IEEE 802.11p protocol I held to provide the best V2V/V2I information exchange among vehicles within a platoon (Li et al., 2019, Aslam et al., 2018, Chen and Park, 2019, Junior et al., 2018).

With regard to the control functional system, communications are predicated on the advanced 5th generation cellular networks (5G). But even more later systems such as CARMA (Cloud-Assisted Real-time Methods for Autonomy) under the “Towards Autonomy - Smart and Connected Control” cluster of on-going projects jointly sponsored by the UK’s Engineering and Physical Sciences Research Council (EPSRC) and Jaguar Land Rover are expected to be come into operation within a few years (Gillam et al., 2018).

It can be inferred from the range of supporting technologies to CAVs implementation – which are in advanced stages of development and testing - that fully autonomous vehicles are technically feasible, and closer to reality than not.

With road geometry effects on CAVs being a novel concept simulation has been found to be an effective and a useful tool, allowing predictions to be made without having to rely on yet-to-be introduced actual driving situations.

Also, at the time of analysing information for this study, CAVs have yet to be released onto mainstream highway networks, hence this precludes access to real data. Simulation and modelling, therefore, were the only techniques that could be used in the current study.

2.2 Vehicle dynamics and control variability

2.2.1 Vehicle modelling research

Lateral control and movement of CAVs have been studied exhaustively. These studies tend to be based on steering systems that use preview theory and model prediction, allowing CAVs to follow a desired trajectory (Chang and Yuan, 2017).

An extensive study at the Ecole Centrale de Lille observed intelligent vehicle control through the adoption of dynamic vehicle models (See Table 2-3). The model used varying road geometry and wind forces, shown in Figure 2-5. Effects of wind on vehicle stability were modelled by resolving the wind forces along a compatible coordinate system to the vehicle model (Yu, 2013).

Table 2-3 Vehicle dynamics model parameters by Yu (2013)

Parameter	Typical value
Mass of vehicle, m	1,250 kg
Aerodynamic drag coefficient C_d	0.5
Aerodynamic side coefficient C_s	0.3
Front area of the vehicle A_F	1.5 m^2
Side area of the vehicle A_s	3.0 m^2
Mass density of air ρ	1.225 kg /m^3
Distance between C.G and front wheels l_f	1.1 m
Distance between C.G and rear wheels l_r	1.58 m
Distance between C.G and centre of aerodynamic force l_c	1.0 m
Yaw moment of inertia I_z	2,872 kgm^3
Cornering stiffness of front/rear tyre $C_{\alpha f}$/ $C_{\alpha r}$	4,200 N/ rad

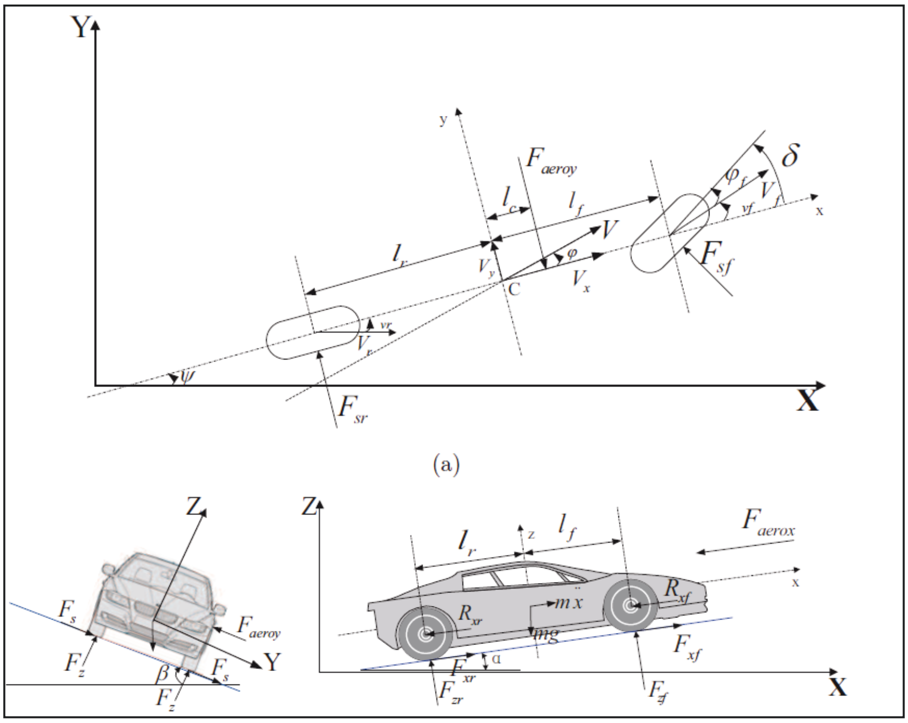


Figure 2-5 Dynamic vehicle model and coordinate system (Yu, 2013)

The road geometry parameters that were found to affect lateral and longitudinal vehicle control were slope and curvature. Figure 2-6 shows that increasing upward slopes increased the time to collision between leading and following vehicles, and that low curvatures also increased the time to collisions.

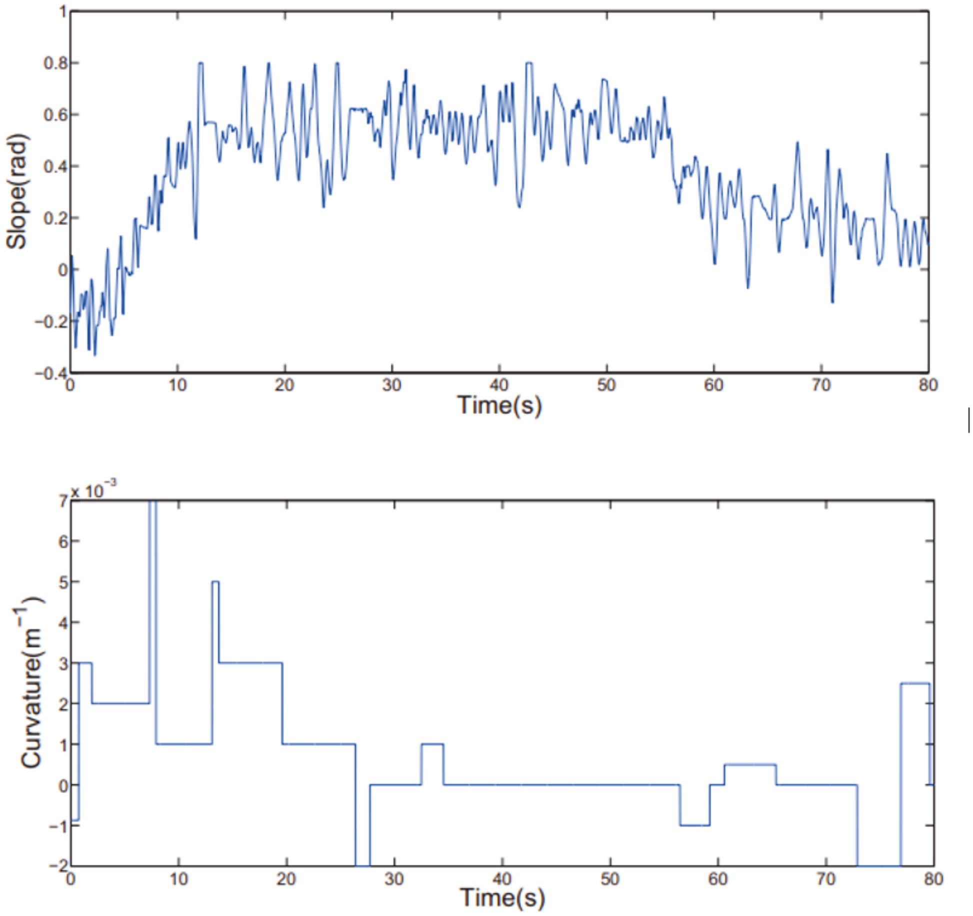


Figure 2-6 Effect of slope and curvature on time to collision (Yu, 2013)

2.2.2 Opportunities and limitations of vehicle dynamic simulations for autonomous vehicles – VIVUS Study

Modelling was also carried out by System and Transportation Laboratory (Lamotte et al., 2010), in which the authors used Virtual Intelligent Vehicle Urban Simulator, or VIVUS, to simulate automated vehicles driving and sensor operations. VIVUS incorporated artificial intelligence algorithms such as platoon solutions and obstacle avoidance devices of AVs. The models involved a 'linear platoon configurations' approaching a new transportation system, shown in Figure 2-7. The results from the VIVUS work is reproduced in Table 2-4.

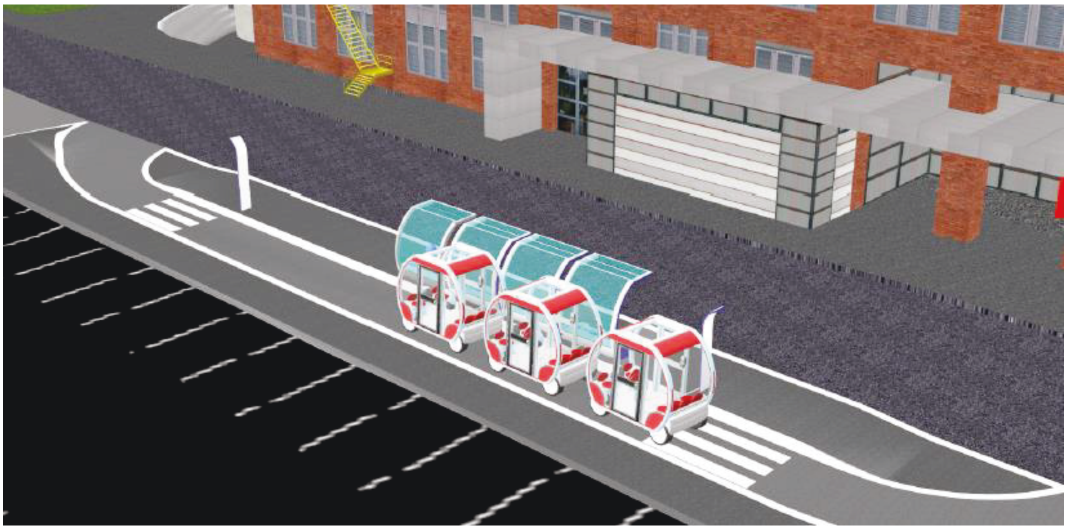


Figure 2-7 Simulating platoon vehicle dynamics (Lamotte et al., 2010)

Table 2-4 VIVUS Simulation versus experimentation (Lamotte et al., 2010)

Wheel rotation (degree)	Curve radius (m)	Medium error in simulation (cm)	Medium error in experimentation (cm)
5.73	18.0	12	30
11.46	9.0	30	40
17.2	6.0	50	46
22.9	4.5	55	55
28.65	3.6	67	70

2.2.3 Deductions from vehicle modelling research

The results of both the Ecole Centrale de Lille and the VIVUS dynamic vehicle simulations showed a direct and significant link between road geometry parameters and lateral vehicle control capabilities. In particular, the road curvature affected the vehicles' ability to maintain its lateral deviation tolerance, with curvier sections leading to larger lateral deviations. Extrapolating from the results of Table 2-4 reveals that straight or near-straight sections will produce negligible lateral deviations.

Since motorways are likely to have large radii or straight sections, it has been assumed for this research that CAVs can execute zero lateral deviations.

2.3 Traffic flow performance

2.3.1 Network capacity parameters

CAV-enabled platooning will result in smaller headways, resulting in increased lane capacity (Makridis et al., 2018b). Subsequently, the traffic flow performance of Level 0 versus Level 5 vehicles will differ considerably, given the inherent role of human-dependent models in underpinning design standards. Specific research has supported this view by asserting that automated vehicles will require significantly reduced reaction times and headways (Segal and Kockelman, 2016).

In other publications, it is shown that CAVs are expected to permit shorter headways through the use of vehicle-2-vehicle communication and platooning, while still guaranteeing safety (Rakkesh et al., 2017, Zegers et al., 2017). Additional studies present a case for time gaps significantly smaller than 1s when co-operative adaptive cruise controls (CACCs) are incorporated within a platoon system (Harfouch et al., 2018).

Specialised research on CACC in platoon trucks further demonstrated the benefits of truck CACC operations through rigorous data analyses. These studies have shown the extent to which enabling direct vehicle-vehicle communication among the trucks in a platoon significantly improves performance. This is especially evident in the shorter following gaps and more stable vehicle flows. The trucks were found to require less road space and were more effective in damping out traffic disturbances in simulations with high market penetration of CACC trucks.

In addition, research carried out by the Zhejiang University, China, quantified the capacity and adjustment factors for multilane carriageways carrying autonomous vehicles. The study was within the context of lateral friction phenomenon, where driving behaviour is influenced by the traffic behaviour in adjacent lanes. The study also included analysing the impact of changing the location of the dedicated AV lane, and found that capacity improved or worsened depending on where within the cross-section that a dedicated lane is implemented for use by CAVs (Qi, 2024).

2.3.2 Effects of platoons on manual vehicles

University of California, Berkley assessed how CACC performs under short- and long-haul peak time trucking situations. They run three AAHSTO Class 8 tractor-trailor trucks (Volvo VNL 440 model) on the Interstate I-710 road corridor (Long Beach Freeway) as the test route. The lead truck was driven by a member of the research team, and the following trucks (second and third trucks) were driven in turn by nine professional fleet truck drivers and their preferred spacings recorded. The effect of the gaps was then simulated. They found that various traffic types, including car passengers, also derive utility benefits from the reduced congestion due to platooning. For trucks, CACC increased average Vehicle Miles Travelled (VMT) by 5.8% and average speed by 19.3%. Cars driving along the corridor (and not fitted with CACC themselves) experienced VMT and average speed increases of 0.7% and 6.2%, respectively. The principal conclusion of this study was that when CACC is deployed to support truck platooning, all vehicles (with or without CACC) on an urban freeway experience appreciable traffic flow benefits (Shladover et al., 2018). However, because these improvements in traffic performance were based on reduced gaps, it could be that the general driving population may be uncomfortable to adopt close following, tempering some of the benefits of CACCs in platoons.

Further research has also found that when mixed with self-driving vehicles, drivers of non-automated vehicles exhibited platoon behaviour by maintaining shorter headways (Merat and de Waard, 2014). The results from these studies show that highway design parameters that account for the operations of CAVs can be less onerous than the current standard requirements without compromising on safety or traffic flow. This advantage of CAVs has been shown by many other researchers using simulations and/or theoretical analysis. Traffic simulation, incorporating Artificial Intelligence algorithms, have been used to show the ability of CACC-enabled vehicles to cooperate for minimised incidents, smoother traffic flow and increased capacity (Bang and Ahn, 2017).

2.3.3 Impact of CAV penetration rates on traffic behaviour

Models based on dynamic and static traffic assignments have been used to show that at low CAV penetration rates, the traffic benefits of CACC systems were insignificant at best (Qom et al., 2016).

In 2016, Atkins published a detailed technical report that outlined the results of traffic modelling of various penetration levels for CAVs (Atkins Ltd, 2016b). The study looked at how increased autonomy and connectivity can influence dynamic vehicle behaviour, including acceleration/deceleration, headways, lateral behaviour, and gap acceptance. This is illustrated Figure 2-8, and shows the impacts of CAVs on the strategic road network incorporating free-flow interchanges. The report concluded that journey times, delays and variability all improved with higher levels of CAVs. All these metrices are affected by lane widths and number of lanes, hence the results support the hypothesis that standard lane widths may be relaxed with no detrimental impact on utility, safety, and traffic flow conditions.

The report, however, makes assumptions of road user understanding CAVs, predicted improvements/stagnation in technology, and impact of a driver's behaviour on other drivers, which are difficult to accurately determine before CAVs are operational.

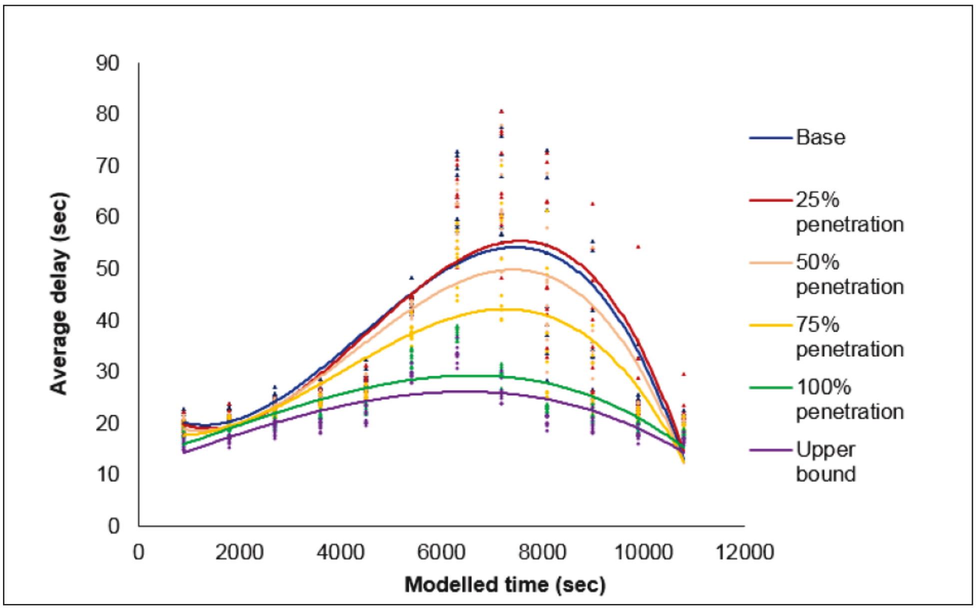


Figure 2-8 VISSIM results showing delay for different MPRs (Atkins Ltd, 2016b)

Furthermore, using a variety of market penetrations, Delis et al. based their traffic modelling on the gas kinetic energy theory to measure the impact of autonomous vehicles on flow conditions (Delis et al., 2016). The simulation results from this work suggest that the presence of ACC and CACC can improve traffic flow stability and increase traffic throughput, particularly at high traffic densities. The study also found that CACC has a greater impact on traffic flow than ACC and that the effectiveness of both systems depends on the penetration rate and traffic conditions.

2.3.4 Traffic flows, connectivity, and headways in CAV scenarios

Capacity and traffic speeds have been shown to increase with increasing proportions of CAVs (Kockelman, 2017). These results are shown in Figure 2-9. Traffic flow theory and fundamental diagram changes will be required. Further research showed that the use of

CACC as part of CAVs can double the throughput at traffic intersections via platooning (Askari et al., 2017, Lioris et al., 2017, Stern et al., 2018).

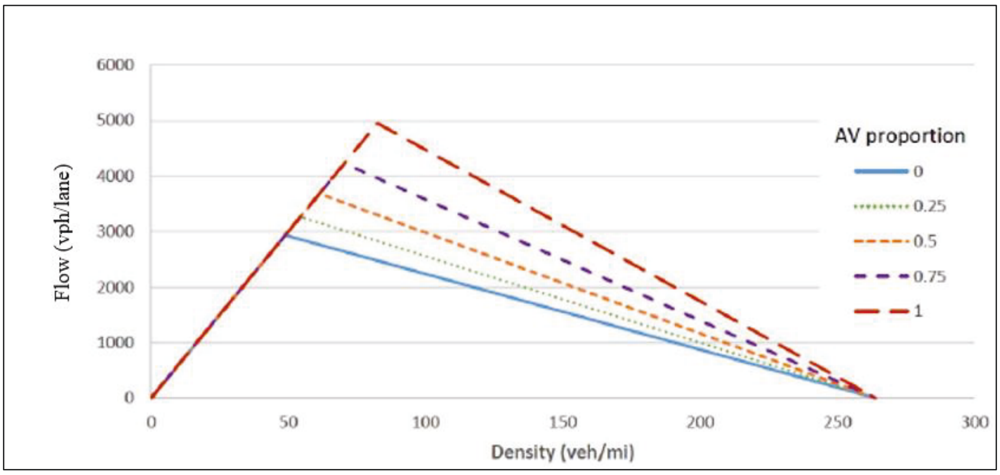


Figure 2-9 Flow-density-AV ratio (Kockelman, 2017)

Although the smallest achievable headway is independent of the penetration rate. It was found that the platoon with minimum headway consists of a group of successive human-driven vehicles and a group of consecutive AV, see Figure 2-10. The mixed platoon configuration that results in the highest headway is when there is alternating AV-human-driven vehicles in the convoy (Ramezani et al., 2018).

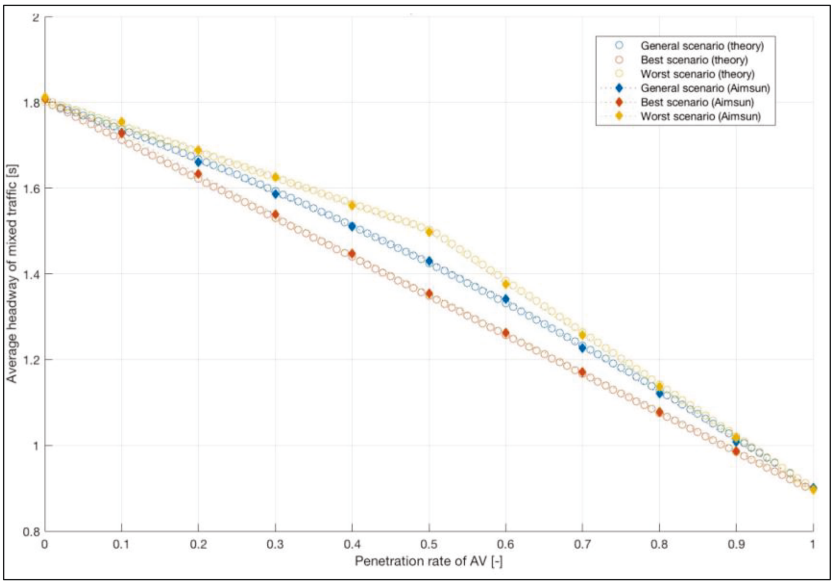


Figure 2-10 Mixed traffic headway, by Ramezani et al. (2018)

When modelled using realistic traffic conditions, CAVs produce a markedly positive impact on the road network with increasing penetration rates (Makridis et al., 2018a).

CAVs immediately behind AVs or manually driven vehicles behave similar to an AV, due to lack of interconnectivity and information transfer. With lower rates of penetrations, CAVs act as AVs, requiring larger headways. At higher penetration rates, each CAV has an increased chance of accessing data from other CAVs. Therefore, traffic flow improves due to smaller headways and gaps, a high harmonic average speed is maintained, and vehicles undergo lane change and merge/diverge manoeuvres much more easily. The traffic streams become far more stable, able to absorb oscillations without traffic breakdown, even for high traffic demands.

Without connectivity (i.e., AV only), it can be seen from Figure 2-11 that as the penetration of the vehicles in the network increases the harmonic mean (or space-mean) speed falls rapidly. Towards the end of the second hour, the network becomes saturated, and with 100% AV, the space-mean speed of the network is 30km/h. During the third hour and the unloading phase, the more congested the network is the slower it recovers. On the other hand, high penetration rates for CAVs shows clearly discernible high harmonic average speed of the network remains at 80km/h. This demonstrates the potential for CAVs to increase the capacity of the network.

At low penetration rates, however, the CAVs do not fully utilise their connectivity as the chances of communicating with other CAVs on the network are reduced. An interesting observation from this study was that for both AVs and CAVs, the harmonic average speed during the initial 1-hour period is lower than the based scenarios of 100% manually driven vehicles. The explanation is that human drivers are less risk averse, taking more risks to achieve higher maximum acceleration, exceed speed limits or approach precarious road conditions less cautiously (Makridis et al., 2018a).

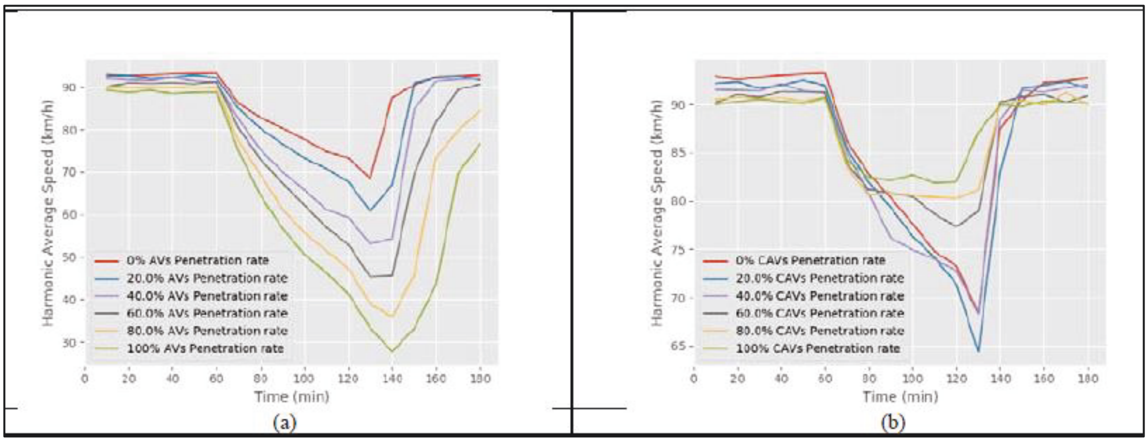


Figure 2-11 Variable AVs and CAVs harmonic speed. From Makridis et al. (2018a)

2.3.5 Traffic delays and road configuration

The traffic delay for different AV penetration rates for each various road cross-section configurations are shown in Figure 2-12. The results show that at AV penetration rate of zero, the dedicated lanes configuration suffers delays similar to that on the 1 AV dedicated lane, 1 mixed lane configuration.

When the traffic composition becomes 100% AV, the delays of dedicated lanes on one hand, and 1 lane dedicated to normal vehicles and 1 mixed lane on the other, are also similar. Minimum delay in the mixed lanes occurs at AV penetration rates of 35%. Hence the configuration that provides optimal traffic flow is 1 dedicated lane and 1 mixed lane.

Another study, which carried out delay and travel time analysis for CAVs found that, the benefit of short headway only occurs when an AV follows another AV, and that the best configuration of mixed traffic would be to provide reserved lanes for AVs. This study also concurred that network performance varied with AV penetration rates (Ramezani et al., 2018).

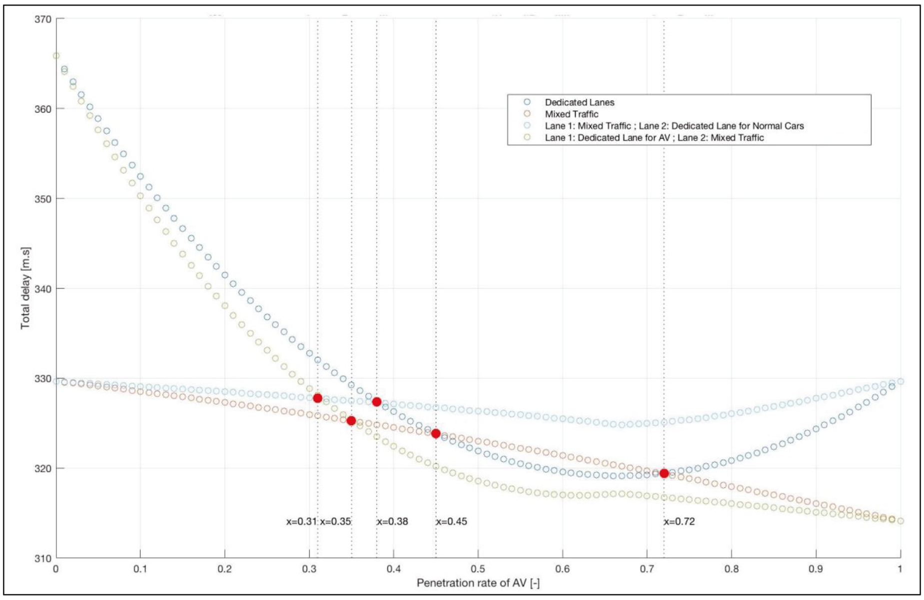


Figure 2-12 Delay by lane configurations and AV rates (Ramezani et al., 2018)

2.3.6 Derived traffic flow assumptions for PhD research.

The research reviewed above show traffic flow performance will differ considerably between Level 0 and Level 5 vehicles due to the role of human-dependent models in underpinning design standards. In addition, it has been demonstrated that CAV-enabled platooning will result in increased lane capacity, due to potential for reduced headways.

The review also emphasises that the introduction of CAVs can minimize incidents, ensure smoother traffic flow, and increase capacity. The fall-out from this conclusion is that lane capacities for dedicated CAV lanes have been assumed to have a capacity twice that of manual lanes, due to the potential for halving the headways. Speeds for CAVs are also taken to not be affected by factors such as lane widths or flow volumes, with autonomous vehicles being able to maintain constants speeds at links, although it is acknowledged that there is likely to be speed variability at junctions due to weaving (merge/diverge manoeuvring).

2.4 Collision reduction and safety benefits

Data collected under varying conditions has shown that accidents that can be attributed to human error is consistently around - or higher than - 90% (Society of Motor Manufacturers and Traders, 2017). Accident statistics are expected to improve with the penetration of CAVs, because fundamental to driverless vehicle systems is the reduced or excluded human control. It has been estimated that over 80% of all road accidents can be avoided or significantly mitigated based on CV techniques (Zhang et al., 2018).

Using numerical modelling within the context of Constant Time Headway Policy (CTHP), specific studies have shown how, in an emergency braking situation, intervehicular communication systems for CAVs can enable vehicles to exchange vital and accurate information within platoons. This reduces the likelihood and severity of collisions (Darbha et al., 2018). However, because these are based on modelling, the results would require validating when CAVs become part of the real work transport system. Nonetheless, these are useful results until post CAVs implementation.

Furthermore, using simulation and vehicle control algorithms to operate a Collision-Free car Following Model (CFFM), a New York University and Chinese Ministry of Education collaboration led to the development of a CACC controller system that provides optimal safety. This CACC system is purported to create a collision-free environment, without adverse impacts on traffic flow (Li and Ma, 2017). Emissions-induced climate change effects

2.5 The contribution of road transport to climate change

Results of extensive data analysis on the sources of greenhouse gases has shown that since the early 1990s, the transportation sector has been the largest contributor to carbon dioxide emissions (CO_2e), annually (Oberthür and Dupont, 2015). Even more pertinent as far as this research is concerned is the fact that road transport accounts for three-quarters of all transport emissions (see Figure 2-13).

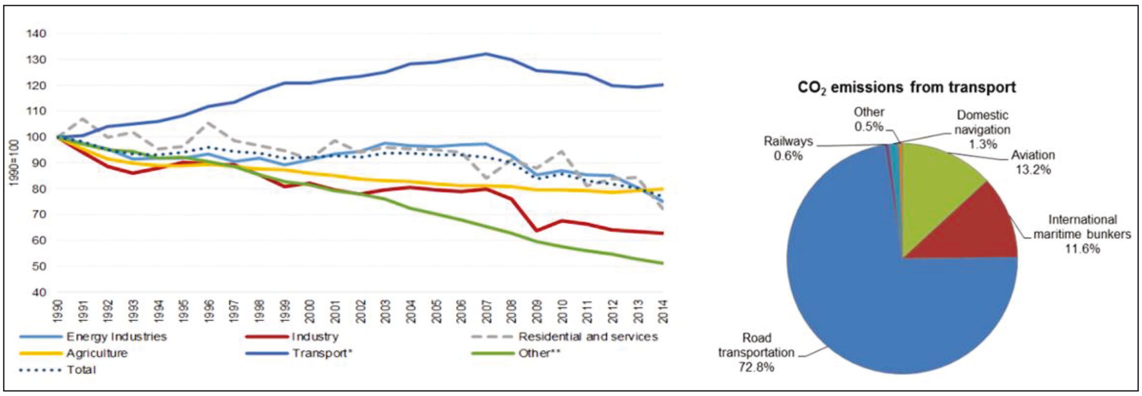


Figure 2-13 Sector and subsector GHG emissions (Oberthür and Dupont, 2015)

The contribution of road transport to harmful greenhouse gas emissions has led the European Union to designate CAVs as a potential major component of the efforts to reduce the rate of climate change.

2.5.1 Identifying opportunities of self-driving trucks as game-changing solution to combating climate change

The European Union's position is that connected autonomous driving can lead to 'higher efficiency of the transport system' (Jagt, 2018). The air drag reduction is likely to be more noticeable in trucks due to the pronounced distortion in pressure zones exerted by larger vehicles. The differences in pressure zone distortion between a single (human-driven) vehicle and close vehicles (such as in experienced in platoons), and its effect on aerodynamic drag is illustrated in (Rakkesh et al., 2017), reproduced in Figure 2-14.

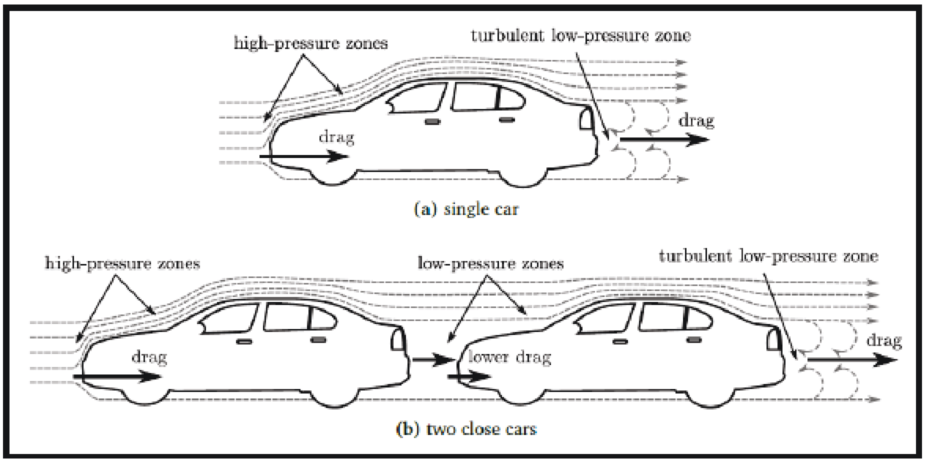


Figure 2-14 Aerodynamics on single and closely followed car (Rakkesh et al., 2017)

2.5.2 Fuel efficiency and reduction in GHG emissions

Fuel accounts for a significant proportion of the running cost of freight vehicles, 25% of which is expended on overcoming aerodynamic drag (Turri et al., 2017). Research based on network-level modelling has also revealed that autonomous vehicle control can result in significant savings in fuel consumptions of up to 8%, with corresponding decrease in harmful GHG emissions particularly Nitrogen Oxides (NOx), Carbon Monoxide (CO) and Volatile Organic Compounds (Mamouei et al., 2018). The results are reproduced in Figure 2-15.

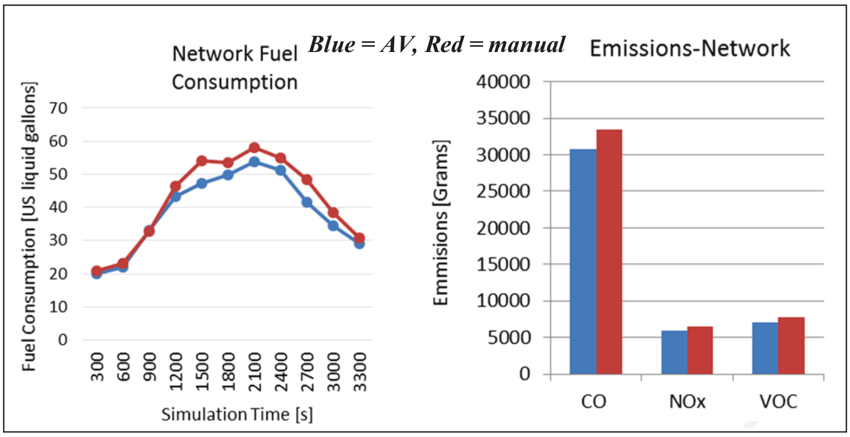


Figure 2-15 Fuel consumption and GHG emissions (Mamouei et al., 2018).

Also, in platoons in which heavy-duty vehicles are operated at short inter-vehicular distances, studies have shown significant reduction in aerodynamic drag, leading to reduced fuel consumption, as illustrated in Figure 2-16 (Turri et al., 2017). This will eventually lead to decrease in greenhouse gas emissions. Coupled with the increase in road capacity, platooning leads to 5-10% reduction in aerodynamic drag and in fuel consumption (Axelsson, 2018).

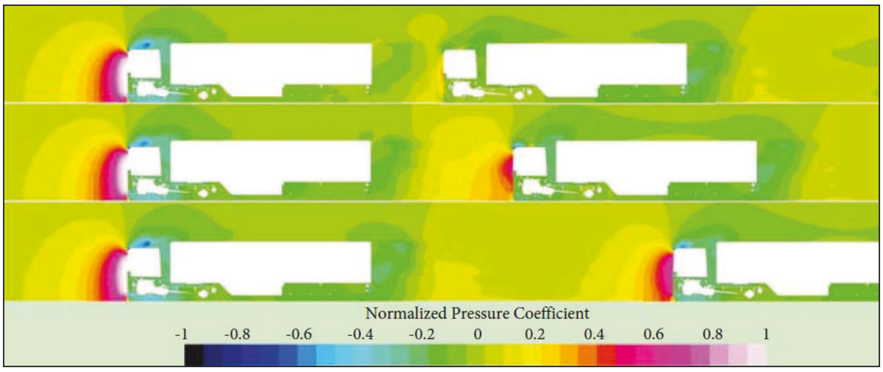


Figure 2-16 CFD, inter-vehicular gaps and aerodynamic drag (Turri et al., 2017)

A research study integrating the US government's Motor Vehicle Emission Simulator (MOVES) models with traffic microsimulations, estimated the fuel consumption behaviour and resulting emissions for truck platoons under test bed conditions (Shladover et al., 2018). The results showed quantifiable reductions in energy consumption can be achieved under steady traffic conditions. This was directly attributed to aerodynamic drag reductions.

Another important contributor to the fuel savings was that the platoon convoy speeds varied much less than for normal traffic. Platoon driving is anticipated to permit vehicles to drive at optimal engine and fuel consumption speeds. The savings achieved for each of the constituent vehicles in the platoon are shown in Table 2-5. The table shows that depending on a vehicle's location within the platoon convoy, and based on an average of 1.4s time gap, a minimum fuel saving of 6.23% and 9.78% can be achieved for Follower vehicles 1 and > 1 respectively at 65mph speeds (Shladover et al., 2018). The study showed that for shorter distances, even higher fuel savings are possible, due to even worse fuel efficiency of stop-start driving experienced in manual driving over shorter distances. No efficiency benefit is experienced by the leading vehicle as the aerodynamic drag coefficient is unchanged.

Table 2-5 Fuel savings for vehicles within a platoon (Shladover et al., 2018).

Position in Platoon	Minimum Fuel saving (%)
Leader	0
Follower 1	6.23
Follower > 1	9.78

2.5.3 Follow-on assumptions and approach to fuel consumption analysis

The review above investigated the potential benefits of connected autonomous vehicles (CAVs) in reducing greenhouse gas emissions by improving the fuel efficiency of the transportation sector. Platooning, in which heavy-duty vehicles are operated at short inter-vehicular distances, can lead to significant reductions in aerodynamic drag and fuel consumption, and eventually to decreased greenhouse gas emissions.

Research shows that autonomous vehicle control can result in significant savings in fuel consumption of up to 8%, with corresponding decreases in harmful greenhouse gas emissions, particularly nitrogen oxides, carbon monoxide, and volatile organic compounds.

The GHG benefits of CAVs is highly significant, giving that the transportation sector has been the largest contributor to carbon dioxide emissions since the early 1990s, with road transport accounting for three-quarters of all transport emissions. The European Union has designated CAVs as a potential major component of efforts to reduce the rate of climate change, as they can lead to higher efficiency of the transport system by reducing aerodynamic drag and fuel consumption. Hence, in modelling the work carried out for this PhD, it was important to be governed by these research publications to improve the reliability of the results.

This notwithstanding, it is important to note that the above studies are based on CAVs being designed in the same way as manual vehicles currently are. Future design of CAVs may be done to improve fuel efficiency with the elimination of space for a driver/steering wheel etc offering some flexibility to achieve this design. However, this study relies on the previous research of like-for-like vehicle designs in order to measure the effects of autonomy alone.

Chapter 3 CONVENTIONAL ROAD DESIGN APPROACHES

3.1 Technical road design overview

Highway designs have traditionally been undertaken to balance various components of infrastructure performance, including safety, environmental impacts, cost, and durability/maintenance requirements, among others. Like many road design codes, current UK standards allow for a degree of inaccuracy and indeterminism inherent in human-controlled driving (Birth et al., 2011, Elliott et al., 2003). This provides a safety margin for road users and enhances infrastructure performance. CATs, however, will lead to more accurate wheel control, and increased predictability of lane choice on multi-lane carriageways. This affects highway designs in these ways:

1. Pavement: Wheel position models affect wheel load stress distribution, and truck lane choice models are used to determine truck volumes in calculations for equivalent standard axle loads (ESALs).
2. Cross-section: Lane widths depend on lateral control capabilities of vehicles and a driver (if present).

Hence, compared to the current MV-based standards for pavement and cross-section designs, there is opportunity for less conservative, more streamlined designs for CATs. Although pavements and lane widths are two fundamentally disparate highway engineering elements, they must be analysed jointly, as their respective performances are mutually interdependent, as demonstrated in numerous studies (Siddharthan et al., 2017, Shafiee et al., 2014, Zhang et al., 2017, Mecheri et al., 2017, McGarvey, 2016).

This Section looks at the historical background to the design approaches for pavement and cross-sections. The section covers the historical developments of current standards in the UK, and then provides a review of the most current design standards.

As with a wide range of highway design elements, pavement and geometry designs standards for major roads in the UK are enshrined in the Design Manual for Roads and Bridges (DMRB).

3.2 Historical development of highway design standards

This section investigates the progression that current highway design has undergone since motorised vehicles entered the transportation system.

3.2.1 The advent of the automobile: from invention to mass production and distribution

In mid to late 1800s, inventors in Germany, France, US, Britain and Australia all stepped up efforts towards producing a motorised transport system that would outperform the horse wagons.

The emergence of self- propelled vehicles led to the UK's first known standard speed limit for vehicles, The Red Flag Act of 1865 (or 'The Man and Red Flag Act'). This was enacted in the UK to restrict vehicle speeds to 2mph in towns, with up to twice that speed permitted in rural areas, see Figure 3-1 for illustration. The Red Flag Act required all self-propelled vehicles to have one person leading the vehicle while waving a red flag to warn other road users such as equestrians, motorists and pedestrians (Graham, 2019).

Further advancements in propulsion technologies led to the first motor vehicles with higher top speeds introduced in 1880. And as a result, the 'Man and Red Flag Act' was repealed in 1896. This removed the speed restrictions, initiating a new era for the motor vehicle, which developed rapidly in the early 20th century (Copson et al., 2019).

Initially, uptake of motorise vehicle technologies was met with resistance as it was very different from the main road transport of the horse-drawn carts. However, right at the start of the 20th century, mass production and distribution had grown exponentially. Cars then became an essential part of military combat during the First World War. Consequently, the immediate post-war years coincided with rapid rise in private car ownership (Lay, 1999).

Figure 3-1 Red Flag Act of 1865 (Graham, 2019)

3.2.2 Evolution of cross-section geometric design standards

This sub-section reviews the development of standard lane widths in the UK. It must be noted that, although the focus of this review is on motorways, earlier technical standards did not have the same distinction between different road classes (i.e., motorway, A-road, B-road, C-Road) as we have them today.

3.2.2.1 Designing new cars to fit existing roads, and new roads to fit cars

Road widths were generally linked to the design speeds, with higher speeds requiring wider roads.

However, the most important determinant of carriageway designs was the existing road. There was a cyclical relationship between road and car designs. Invariably, the outer dimensions of cars were designed to fit the existing roads. Once these cars were mass-produced, new roads being designed then had to be suitable for the dimensions of the cars.

3.2.2.2 Original design standards

The transition towards relatively faster motor vehicles coincided with the production of the earliest forms of highway design standards. The oldest version discovered during this study was published in 1930 as *Memorandum 336 (Roads) – Notes on the Layout and Construction of Roads*. Intended for the design of major road schemes in the UK, these first edition standards specified suitable highway geometric design values (Ministry of Transport, 1930).

Cross-sectionally, the document prescribed the use of 9ft (2.74m) wide traffic lanes, much narrower than today's 3.65m. Although *Memorandum 336* was targeted at dual carriageways, no dimension is specified for central reserves. At the time, the document did not require the provision of hard strips/hardshoulders, a significant safety feature in modern road designs standards.

3.2.2.3 Emergence of motorways and the lingering legacy of horse-drawn carts

By the middle of the 20th century, motorways were beginning to be designed and constructed in Britain. This led to the publication of technical standards targeted at this new class of road. A pamphlet titled *Circular to Divisional Road Engineers No. 46/53. Motorway Standards* was released to provide advice on the latest design standards specifically for motorways.

This circular referred to 22ft (6.70m) and 30ft (9.14m) dual motorways. It also specified a hard strip ("margin") of 1ft. For 2 lanes, this suggests lane widths of 11ft (3.35m) each plus the 1ft (0.30m) offside and nearside hard strip. And for 3 lanes, 10ft (3.05m) each with 0.30m hard strips. The recommended central reserve width was 10ft (3.05m) (Ministry of Transport, 1953).

Motorways were purposefully designed for safer travel at higher speeds, and this can be clearly seen in the wider lane widths, as well as the introduction of nearside safety margins and offside central reserves. However, no authoritative research could be found to justify the choice of these early lane widths or other cross-sectional elements.

Notwithstanding this, it is well established that there are substantial technical similarities between the first century Romans roads in Britain, and current UK motorway network. (Wall and Hounsell, 2004). These similarities suggest that the early motorway standards were influenced significantly by the pre-automobile transport modes, despite being developed well after the invention of the automobiles. A likely explanation would be that the standards were developed to fit the ancient road system so that extensive road reconstruction is minimised.

3.2.2.4 Adaptation of comprehensive design manuals

Subsequent years then saw a noticeable shift in the way technical standards were published, with a move away from circulars and pamphlets to more comprehensive highway design manuals.

Towards the end of the 1960s, a manual titled *Layout of Roads in Rural Areas* was published intended to equip highway engineers with the skill and knowledge to produce technically sound and economically balanced designs. This manual described the design approach to be used for motorways and dual carriageways (Ministry of Transport, 1968). The widths for the various cross-sectional elements were:

- Traffic lane: 12ft (3.65m)
- Central reserve: 13ft (3.96m)
- Hard shoulder: 9ft 6’ (2.90m)
- Verge: 5ft (1.5m)

These dimensions are shown in Figure 3-2.

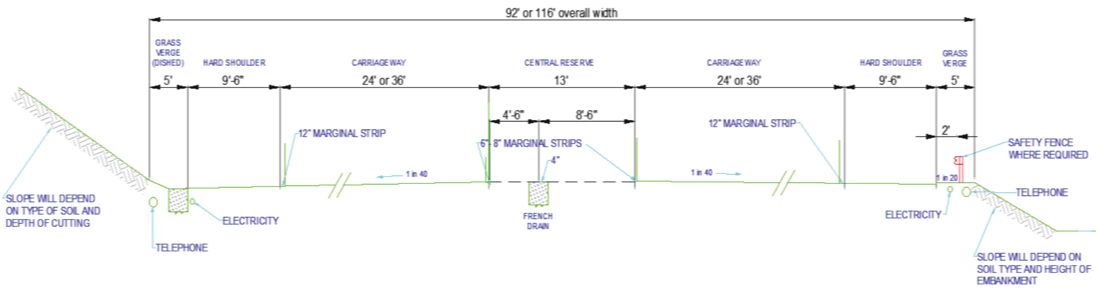


Figure 3-2 Motorway section 1968 to 1987. Redrawn from Ministry of Transport (1968)

3.2.2.5 Creation of the Design Manual for Roads and Bridges suite

In 1988, the first edition of the DMRB standard for road cross-sections was published (Department of Transport, 1988). This superseded the principal highway link and cross-sectional design parameters in the previous advisory manual for motorway design (Ministry of Transport, 1968). As shown in Figure 3-3, the pioneering version of DMRB specified motorway lanes widths to be 3.65m, with 3.30m hard shoulders. The central reserve width within this standard was specified as 4m wide, along with 1.50m verges.

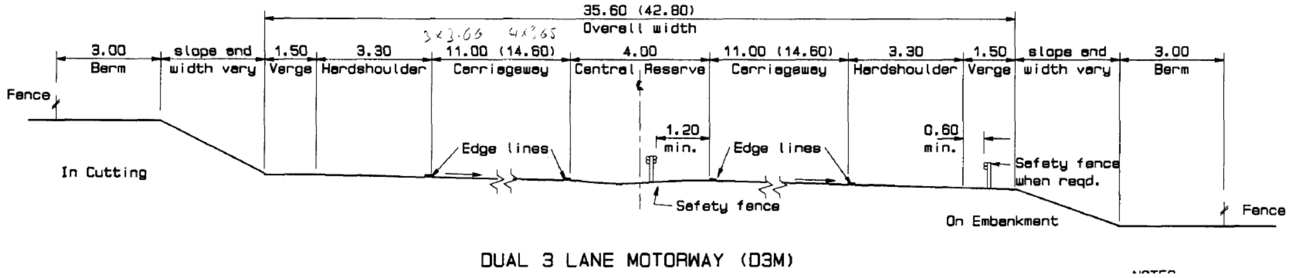


Figure 3-3 Highway details in first TD27 (Department of Transport, 1987)

The cross-section dimensions from the first DMRB were maintained in a subsequent revision in the mid-1990s, except that the 3 lanes did not have equal widths, with the offside lane being the widest at 3.75m, followed by the middle lane at 3.65m, and then the nearside lane at 3.60m (Department of Transport, 1996). This is shown in Figure 3-4.

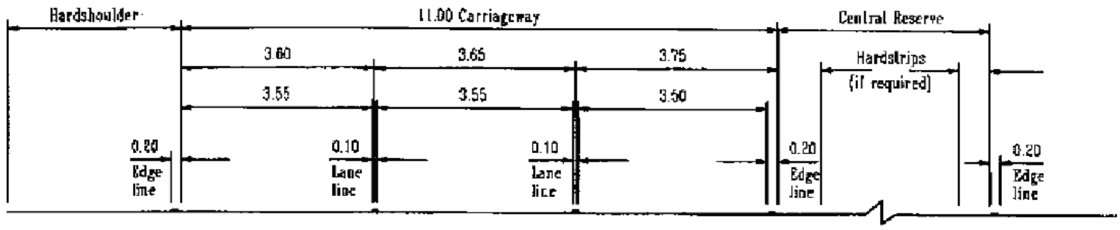


Figure 3-4 First DMRB with specific, unequal lanes (Department of Transport, 1996)

The next revision of DMRB cross-section dimensions was then released in 2007 as TD27/05 (Department of Transport, 2007). Widths for the different elements in this version have been maintained in the current version of the DMRB, CD127 (Highways England, 2020f). As shown in Figure 3-5 below, the current standard for dual 3-lane motorway (D3M) would have a 3.70m middle lane, and 2no. 3.65m outer lanes. A 3.30m nearside hardshoulder will also form part of the paved carriageway for emergency use and as a safety margin, with a 1.5m wide, unpaved verge for locating various highway features. The un-trafficked offside elements will be made up of a 0.70m hard strip and a 3.10m wide central reserve. The current DMRB lane widths are specified to allow for imprecise human steering (Department of Transport, 2007).

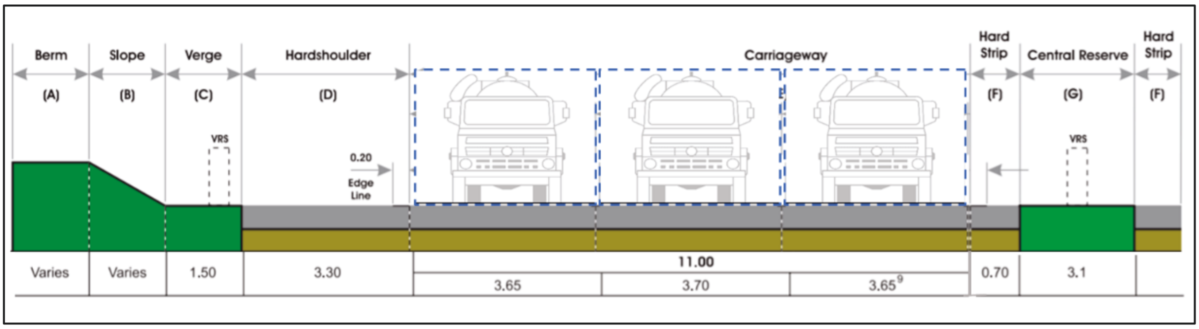


Figure 3-5 Current standard cross-section. Modified from Highways England (2020f)

Slightly narrower dimensions (down to minimum of 3.30m offside lane) are permitted for Smart Motorways, and where significant constraints restrict existing carriageway widening.

3.3 Pavement design methods

A major objective that must be achieved by roads is structural stability of the running surface, which is accomplished by appropriate pavement design for the anticipated vehicle loadings. Pavement is one of the most important elements of road infrastructure schemes as they constitute a substantial proportion of the initial conversion cost (Capital Expenditure, or CAPEX). Pavements also incur a high maintenance cost as they require regular rehabilitation – the need to maintain acceptable safety and operational performance means resurfacing could be carried out every 2-5 years (Nicholls et al., 2010). Given their technical and economic significance, analysing the effects of CAVs on pavements require utmost attention in the transportation research space.

3.3.1 Theoretical basis to structural pavement designs

Pavements consists of upper structural layers which bear the imposed wheel loads from traffic, and the lower foundation layers which protect and/or strengthen the existing ground against excessive deformation. Although there are other innovative and specialist pavements such as interlocking block and modular cellular pavements, the UK design standards provides guidance for 3 conventional pavement types: flexible, rigid, and composite pavement systems. This taxonomy is based on the material properties of the constituent layers, which in turn determine the load-bearing and structural failure mechanism.

Flexible pavements use a system of superimposed layers of processed asphalt materials installed on the foundation layers. The main structural layer is the Roadbase, and this is then overlaid with a Binder Course (or Base Course) which supports the relatively thinner Surface Course layer to provide suitable ride quality to motorists, anti-skidding through tyre-road interaction, and crack resistance. The asphalt materials are made of aggregates bound by bituminous materials. Coupled with the foundation, the resulting asphalt concrete material distributes applied traffic loads such that the residual stresses transmitted do not exceed the bearing capacity of the sub-grade. The pavement achieves this by transferring wheel loads imposed on the surface via grain-to-grain contact through the granular structure of the pavement, down to the lower layers (The Contact Patch). This phenomenon is illustrated in Figure 3-6 below.

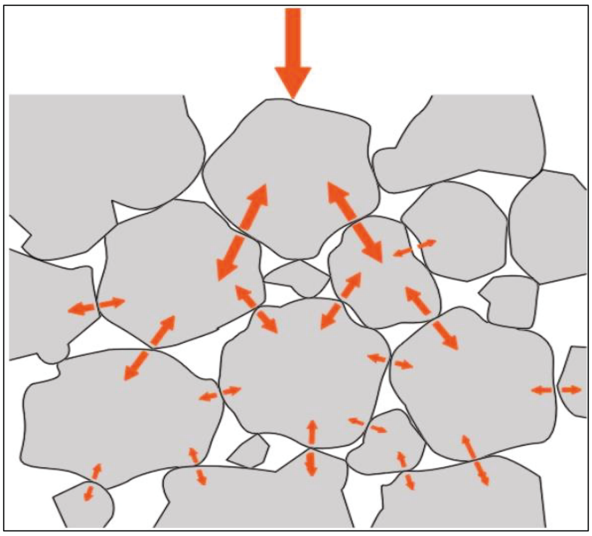


Figure 3-6 Traffic wheel load dispersion in granular pavement structures (The Contact Patch)

Soil theories have long been the accepted models for analysing the behaviour and response of flexible pavements subjected to imposed loads. Boussinesq first developed a set of equations to calculate the stresses and strains induced by a point load within a homogeneous, elastic, isotropic half-space medium. These equations were based on uniformly loaded circular area similar to the wheel loading of vehicles traversing flexible pavements (Molenaar, 2007). Boussinesq theory showed the decay of stress underneath a wheel load laterally, and with depth in cartesian and cylindrical coordinates, see Figure 3-7.

Burmister subsequently provided a solution for stresses in a two layered system, establishing that induced vertical stresses are influenced by the ratio of material stiffness between the upper and lower layers, with a higher ratio (i.e., stiffer upper layer) reducing the magnitude of vertical stress with depth. Burmister's theory forms the basis for the design of flexible pavement systems, extended to multi-layer systems, see Figure 3-8. The principle behind this theory for multi-layer pavement systems is that, for a given sub-grade strength, stresses at the interface between the top and lower layers can be reduced by increasing the thickness and/or stiffness modulus of the upper layers (Molenaar, 2007).

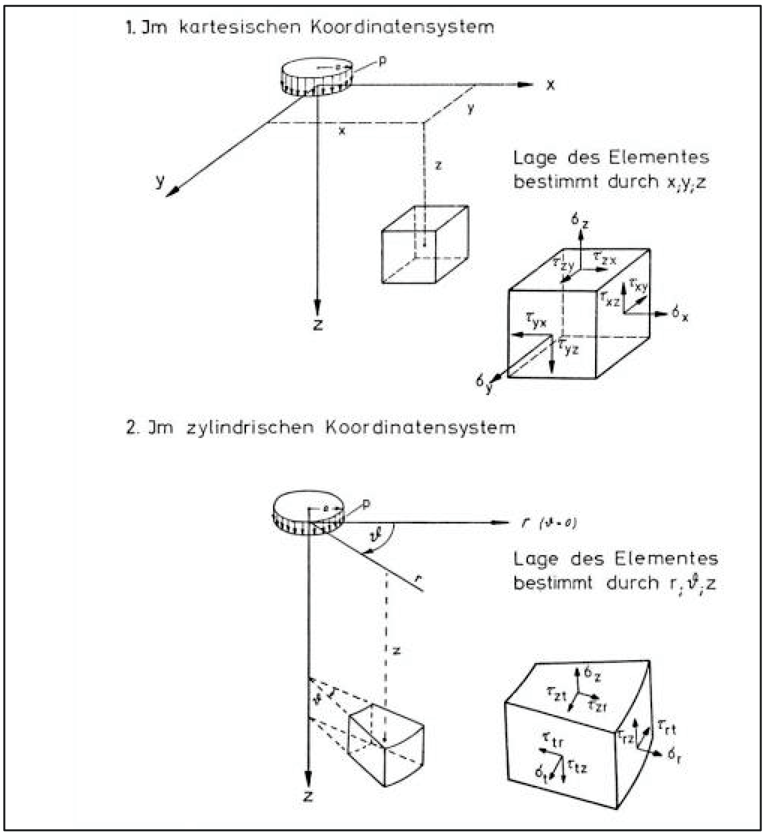


Figure 3-7 Boussinesq theory. From Molenaar (2007)

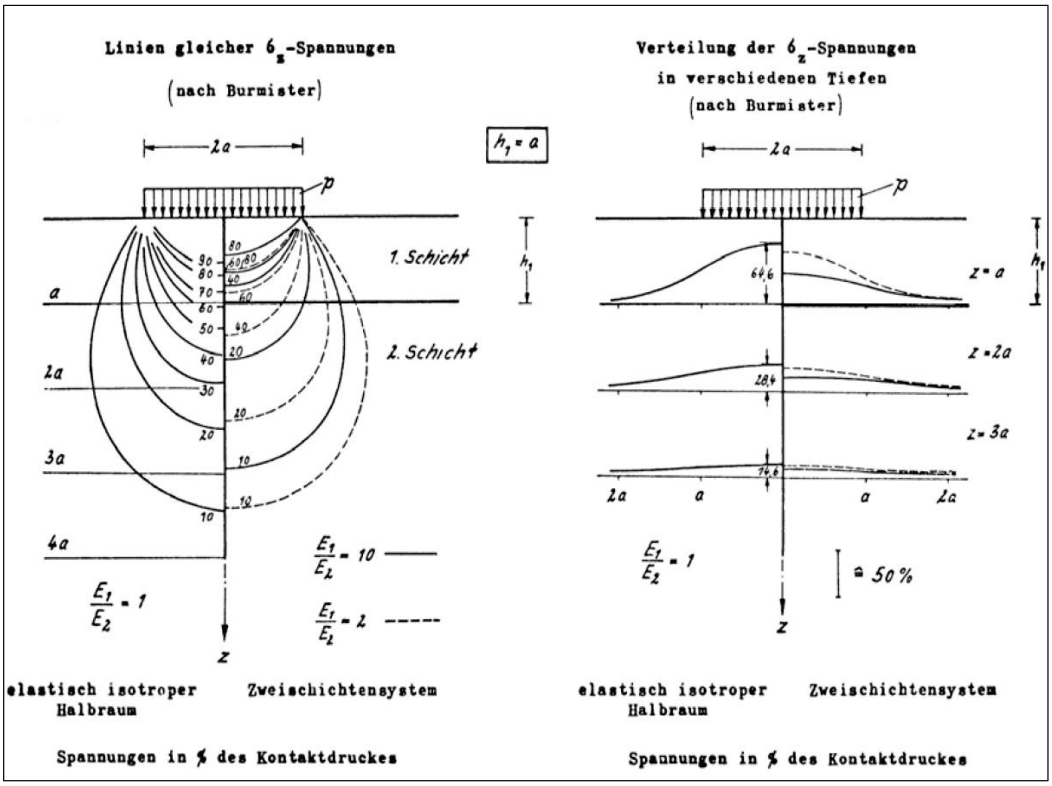


Figure 3-8 Burmister’s 2- and 1-layer stress distribution: From Molenaar (2007)

The critical stresses that govern flexible pavement failure are horizontal tensile strain induced at the underside of the bound bituminous layers, and vertical compressive stress which occurs at the top of the subgrade (Powell et al., 1984). The locations of these stresses within the pavement, and their positions relative to the applied load, are shown in Figure 3-9.

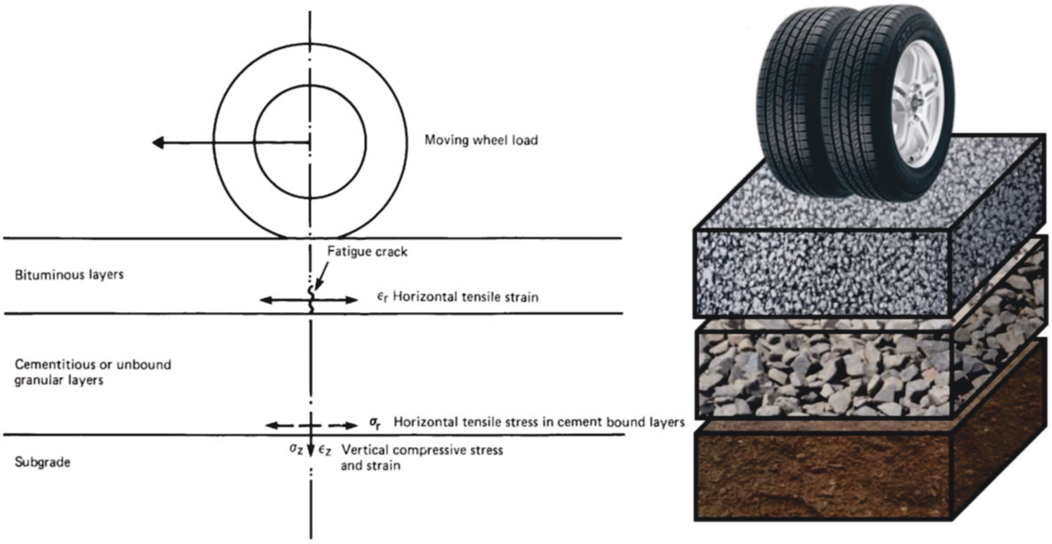


Figure 3-9 Critical asphalt pavements failure stresses. Adapted from Powell et al. (1984)

The horizontal strain and vertical stress manifest as fatigue reflective cracking (due to fracturing) and permanent deformation, or rutting (due to shear distortion, creep or densification) respectively. In theory, failure is deemed to occur when the imposed traffic wheel loads generate high enough stresses that cause cracking and/or rutting.

3.3.2 UK design standard

The UK method uses the Load Equivalency method to relate pavement deterioration to vehicle loading during the pavement's design life. The traffic predicted to use the pavement during the pavement's design life is converted into an equivalent number of 'standard' axles. The pavement materials and thicknesses of construction layers are then read from design charts. Each class of vehicle is assigned a wear factor to convert its loading into a number of equivalent standard axles, which would apply the same loading to the pavement. This method forms the bases of most major international pavement design standards. It is a tried and tested method which allows analytical design, and permits changes to materials and vehicles (TRL Limited, 2006). The load equivalency is considered the most robust and practicable for use in industry.

The main UK standards for pavement designs are:

- DMRB CD 224 – Traffic assessment
- DMRB CD 226 – Design for new pavement construction, and
- DMRB CD 225 – Design for new pavement foundations

These standards utilise studies on asphalt pavement performance data collected over several years, combined with the structural theory associated with the material properties of the various layers. The DMRB design standards enable designers to apply both empirical and analytical design approaches (Brown, 2013).

3.3.2.1 Imposed load calculations

DMRB provides a method for calculating vehicle traffic loading. The input parameters required for this calculation are:

- Commercial vehicle flow
- Wear factor
- Design year
- Growth factor

- Percentage of vehicles in the heaviest loaded lane

The first step involves applying pavement structural wear factors to the total volume of various classes of commercial vehicles (Highways England, 2020e). See Table 3-1 for current DMRB standard wear factor values. This provides traffic loading expected at the time the road is open to traffic. To calculate total traffic loading that the road will be required to withstand over its design life, a design period (usually over 20 or 40 years) is then selected. A traffic growth factor is then applied to forecast the total design traffic loading over the design life of the pavement structure. The DMRB recommended growth factors are reproduced in Table 3-2.

Finally, a distribution factor, P, selected from Table 3-3 below, is applied to calculate what percentage of the commercial vehicles will use the most frequently traffic lane. The entire pavement cross section is then designed to withstand the loads imposed on the heaviest road section.

Table 3-1 Vehicle damage factors. From Highways England (2020e)

	Maintenance W_M	New W_N
Buses and coaches	2.6	3.9
2-axle rigid	0.4	0.6
3-axle rigid	2.3	3.4
4-axle rigid	3.0	4.6
3 and 4-axle articulated	1.7	2.5
5-axle articulated	2.9	4.4
6-axle articulated	3.7	5.6
OGV1 + PSV	1.3	1.9
OGV2	3.2	4.9
All commercial vehicles (70% OGV2)	2.7	4.0

Table 3-2 Standard traffic forecast growth factors. From Highways England (2020e)

Design period (years)	5	10	15	20	25	30	35	40
OGV1 + PSV	1.02	1.05	1.08	1.11	1.14	1.17	1.21	1.24
OGV2	1.04	1.10	1.16	1.23	1.30	1.37	1.46	1.54
All commercial vehicles	n/a							1.45

Table 3-3 Vehicles ratio in the heaviest loaded lanes. From Highways England (2020e)

Number of lanes (in one direction)	Flow (F) (cv/day)	P (%)
2 or 3	Up to 5,000	P = 100 - (0.0036 x F)
	Over 5,000 up to 25,000	P = 89 - (0.0014 x F)
	Over 25,000	P = 54

3.3.2.2 Structural layers

DMRB CD 226 (Highways England, 2020d) then presents design charts, for which the calculated vehicles loads are to be used to obtain pavement structural layer materials and thicknesses, see Figure 3-10. This standard was produced to standardise the findings from a comprehensive and detailed TRL research on flexible and composite pavement systems (Nunn, 2004). The TRL report detailed a versatile method to designing pavements which uses wider range of material properties of the various pavement layers, allowing for a more localised analysis of stresses in individual layers.

For fully flexible pavements, the method uses a linear elastic, multi-layer pavement response model to determine critical stress or strains within the pavement structure, when a single standard wheel load of 40kN is distributed as a 0.151 radius circular patch with a uniform vertical stress (Brown, 2013).

The satisfactory structural performance is that the pavement layers must not crack under the traffic load, i.e., the horizontal tensile stress or strain at the bottom of the base must not exceed the critical pressure that causes the crack, as demonstrated in Figure 3-11. In other words, the flexural stress or strain at the underside of the base layer should be limited to the permissible level to achieve the required pavement life. This is a fatigue failure criterion.

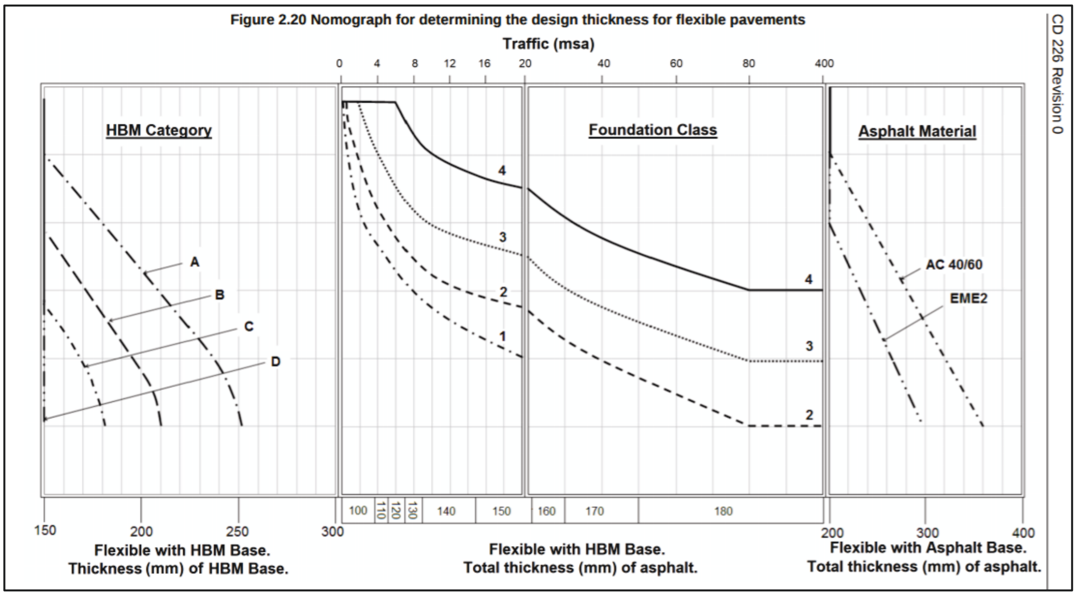


Figure 3-10 Standard flexible pavement design charts. From Highways England (2020d)

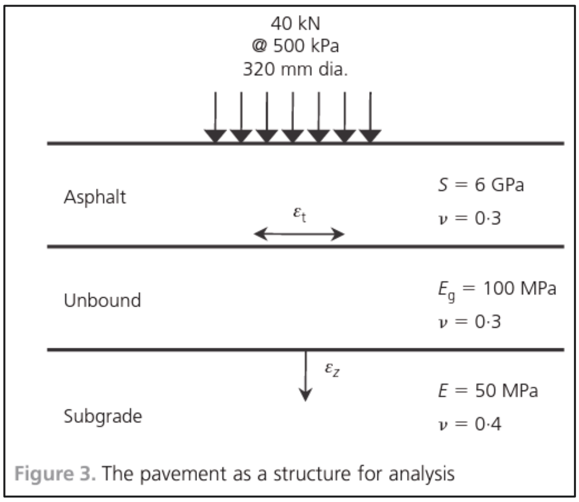


Figure 3-11 Conceptual pavement analysis structure (Brown, 2013)

The current method is analytically based for all traffic levels, and only considers the traffic induced stresses at the underside of the base layer. It is this sole consideration of traffic induced stresses that makes it important to assess the impact of wheel track load distribution on traffic stresses, and hence pavement designs. This stress at the underside of the base layer is multiplied by two factors: K_{Hyd}, the material specific calibration factor which includes temperature effects, curing behaviour and transverse cracking characteristics, and K_{Safety} a factor of safety depending on level of design risk. Default is 1.0.

Typically, due to uncertainty in actual traffic volumes on a highway, all travel lanes are constructed with equal thickness, which is generally determined based on the lane with the highest estimated traffic volume. However, with segregated traffic lane configurations for autonomous vehicles, there should be more confidence in assigning traffic volumes that will use certain lanes.

3.3.2.3 Foundations

Once the structural layers are designed, CD 225 is then used to design pavement foundation, based on sub-grade strength. This is generally exclusively a function of the bearing capacity of the existing ground. Hence, the peculiarity of CAVs loading is not expected to affect this aspect of pavement design, as foundations will still likely be designed based on the prevailing ground properties.

3.4 Limitations in current analytical basis for pavement design

The current wear factors and lane distribution models in UK pavement design methods are not tailored to the introduction of connected autonomous trucks. The procedure does not also enable variable lane widths to be used to adjust pavement designs.

3.4.1 Wear factors

In reviewing the DMRB traffic load calculations against the introduction of CAVs, it is worth noting that the development of the standard wear factors is based on distribution of traffic in heaviest traffic lane. The method relies on a damage load equivalency approach, which is based on the damaging effect of vehicles of certain axle loads and configuration (TRL Limited, 2006). The method was developed by collecting and analysing data on structural pavement damage from vehicles, all of which were manually driven, and would have been based on manual vehicles wander distribution models.

Conservatism was also built into these wear factors, including traffic composition, speed, and other factors. But the lateral wheel position of CAVs can be more closely controlled, hence the wear factors may not be suitable for autonomous vehicles.

3.4.2 HGV lane distribution model

There are existing research publications which allow more flexible modelling of HGV distribution in lanes. Also, it is possible to more strictly direct CAVs to particular lanes, increasing the distributional certainty in lane utilisation. This could proof significantly beneficial to highway designs.

This application of 'worst case loading scenario' to the whole cross section implies that current standard pavement designs are conservative, and potentially inappropriate for CAVs. The use of this conservative approach is justified by its proponents on the basis that lane choice is indeterminate.

However, with the introduction of CAVs, most of the commercial vehicles should traffic the nearside lanes of multi-lane carriageways due to legislation, which prohibits any heavy goods or high-occupancy passenger vehicles weighing at least 7.5 tonnes to use the outermost lane, except when overtaking (UK Government, 1982, UK Government, 2015).

The likely increased compliance of CAVs to highway legislation should reduce or eliminate the uncertainty in the distribution of heavy vehicles. This will provide opportunity to tailor pavement structural designs to individual lanes. Even for manual vehicles for which driver choice is more complex to accurately model, research indicate a high level of compliance of HGV drivers staying to Lane 1.

Research was carried out to determine the actual vehicle distribution of HGVs in traffic lanes, showing that, for 3-lane motorways, the proportion of HGVs in each lane closely followed a model that was strongly correlated to HGV and total flows, see Figure 3-12 (Yousif et al., 2013).

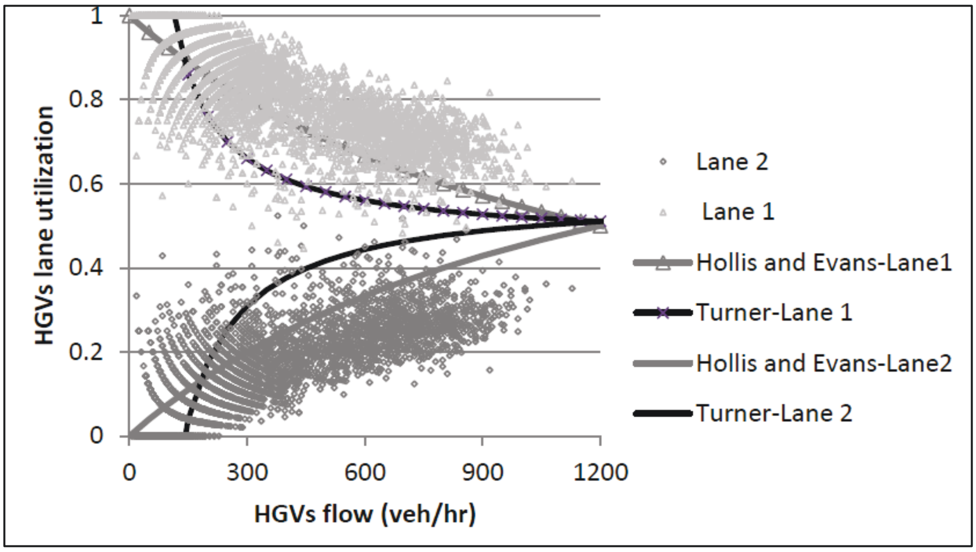


Figure 3-12 HGV distribution: models-real data comparison (Yousif et al., 2013)

The models obtained from this study are:

$$P_H1 = 0.976 - 0.0002044H - 0.0000285q \qquad \text{Equation 3-1}$$

$$P_H2 = 1 - P_H1 \qquad \text{Equation 3-2}$$

$$P_H3 = 0 \qquad \text{Equation 3-3}$$

Where H is the number of HGVs, and q is total flow.

The r^2 in Lane 1 and Lane 2 were 0.70 and 0.63, respectively. For a typical 3-lane motorway in the UK, applying this model shows that 80% of HGVs use Lane 1, while 20% use Lane 2. Crucially, the HGV utilisation for Lane 3 on a 3-lane motorway is zero. This means there are opportunities to implement thinner pavements in Lanes 2 and 3, by reducing the total asphalt layers.

Figure 3-13 illustrates how this variable pavement thickness could be implemented across the carriageway by reducing the total asphalt layer from 360mm to 200mm, based on minimum loading of 80msa in Lane 1. A transition zone needs to be provided, with the thicker layers reducing gradually at a 45^{o}, to avoid differential settlement.

Although the slanted layer interface between Lane 1 and Lane 2 for the sub-based and base course could introduce some construction difficulties, as large drum roller compactors may be unable to work along such steep slopes. Other compaction methods such as hand-held compaction equipment would be required to achieved sufficient material compaction, and this could prolong the construction duration.

Interfacing between different pavement thicknesses occurs regularly in construction, for example, when a minor estate road joins a busy major road. Overall, the reduced material and excavation costs should outweigh disbenefits from the sloped interfacing.

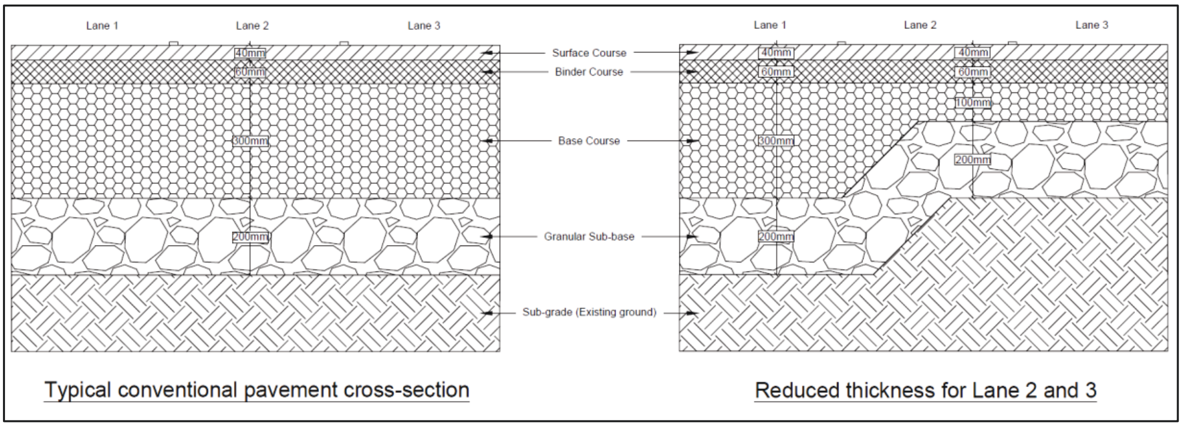


Figure 3-13 Conventional and reduced pavement thickness

Other studies developed alternative lane distribution models, as shown in Figure 3-14 (Brackstone et al., 1998).Specifically, the authors used logistic regression models to estimate the probability of a vehicle changing lanes based on a number of factors, such as vehicle type, speed, headway, and the presence of other vehicles. The models were estimated separately for each lane and direction of travel.

The dependent variable was the probability of lane changing, while the independent variables included a range of vehicle, driver, and traffic characteristics. The models were estimated using data collected from video recordings of motorway traffic in the UK.

The results of the regression models showed that several factors had a significant impact on lane changing behaviour, including vehicle speed, headway, and the presence of other vehicles in adjacent lanes.

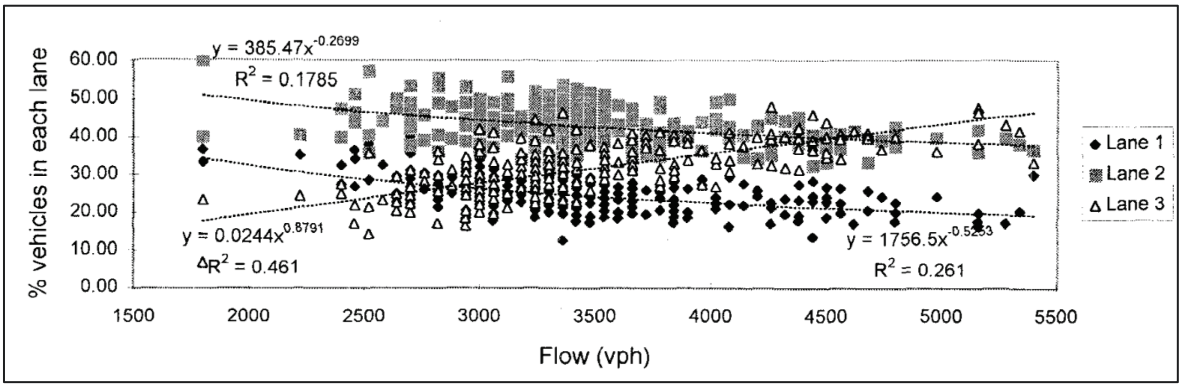


Figure 3-14 Observed lane distributions regression models (Brackstone et al., 1998)

The regression models demonstrated that percentage of vehicles in lanes 1 and 2 both decrease with increasing flows; percentage in lane 3 increases with flow.

Clearly, the vehicle distribution models are currently highly variable and based on human responses to traffic conditions. These need amending for CAT traffic.

3.4.3 Lane width as an omitted pavement design parameter

Pavement performance has been shown to be considerably affected by lane widths (Siddharthan et al., 2017, Shafiee et al., 2014, Zhang et al., 2017, Mecheri et al., 2017, McGarvey, 2016). In addition, pavement design and analysis information produced by the Research for Community Access Partnership (ReCAP), provides a relationship between road widths and effective damage factors, showing that differences in lane widths can results in 350% increase in pavement damage (Pinard and Hongve, 2020).

Due to this interdependence, specific national highway design standards, such as that of the Netherlands, incorporate a lane width factor in pavement structural design to account for the lateral position of vehicles and load distribution. The basis for the Dutch model is that narrower lanes cause wheels to follow a narrow path, which leads to a concentration in wheel load, known as channelisation. Wider lanes have the opposite effect (Atkinson et al., 2006).

Yet there is no provision within the current UK pavement design standard to incorporate effect of varying lane widths.

3.5 Summary on development and limitations of standards for CAVs

Connected autonomous vehicles are expected to behave fundamentally differently from manual vehicles. Differences in the attributes of CAVs which could affect highway engineering designs include perception-reaction times, vehicle wheel wander, distribution and lane occupation models, adherence to stipulated speed limits, congestion and maximum capacities, accident models and fuel consumption.

Although design standards have evolved since the first motorised vehicles emerged as a main part of transport, these still do not include the effects that connected autonomous driving, as opposed to a human driver, would have on key design parameters. Table 3-4 summarises the journey that cross-section design standards have been through, up to the current standards. This shows that, although the DMRB has been recently revised, key parameters governing geometric and pavement designs still use data collected from manually driven vehicles. No account is made for autonomous vehicle driving.

Current standards on lane widths designs, which directly affect pavement deterioration, use historic data and manual vehicles. This means, the determinate lane distribution models that CAVs are expected to exhibit are not included in pavement design analysis, neither is their precise wheel tracking or uniform wander capabilities. CAVs are yet to be introduced, hence no historical data exists that can be used in pavement analysis, as is currently done for manual vehicles. Simulations and predictions would have to be used to amend these parameters and develop new pavement design models.

To conclude, therefore, the current motorway design standards in the UK are largely a product of research into human driving behaviour adjusted to account for human errors and variability within the context of providing faster yet safer roads, and a legacy of the ancient Roman road system.

Table 3-4 Evolution of standard cross section design parameters

PERIOD	**1930-1953**	**1953-1968**	**1968-1987**	**1988-1996**	**1996-2007**	**2007-2020**	**2020-date**
STANDARD	**Memorandum 336**	**Circular 46/53**	**Layout of Roads in Rural Areas**	**DMRB TD27/86**	**DMRB TD27/96**	**DMRB TD27/05**	**DMRB CD 127**
COMPONENT (m)							
Lane 1	2.74	3.05	3.65	3.65	3.60	3.65	3.65
Lane 2	2.74	3.05	3.65	3.65	3.65	3.70	3.70
Lane 3	2.74	3.05	3.65	3.65	3.75	3.65	3.65
Hardshoulder	-	0.30	2.90	3.30	3.30	3.30	3.30
Verge	-	-	1.50	1.50	1.50	1.50	1.50
Central reserve	-	3.65	3.96	4.00	4.00	4.50	4.50
Carriageway	8.22	9.15	10.95	10.95	11.00	11.00	11.00
Cross-section	16.44	22.55	34.66	35.50	35.60	36.10	36.10

Chapter 4 ASSESSING HIGHWAY ENGINEERING DESIGN FOR FULL AUTONOMY

The assessments in the preceding chapters have explained that road design parameters are deduced using human driver-related factors. This viewpoint is consistent with universal principles of highway design (Birth et al., 2011). Whereas pavement design standards are influenced by drivers' vehicle control abilities and lane choice, the origin and evolution of motorway designs standards shows that safety is central to the selection of geometry design parameters.

In this Chapter, a systematic review has been undertaken to establish what research currently exists around how highway designs are impacted by CAVs. As was done for the previous chapter, the focus is on pavements and geometric designs.

4.1 Existing research on pavement structural integrity under CAV loading

This section reviews recent research into how connected autonomous driving is predicted to impact on pavement performance.

4.1.1 Quantifying CAV pavement failure modes

4.1.1.1 Development of novel methods for investigating correlation between pavements and connected autonomous vehicles

A 2017 study by Arizona State University (ASU) has been generally accepted within the pavement analysis research community as the pioneering publication quantifying the impact of autonomous trucks' wheel lateral control on pavement. The study devised a method for including uniformly distributed truck positioning into pavement design and analysis models. (Noorvand et al., 2017).

The methodology used computer simulation to optimise pavement deterioration. Using pavement performance prediction models within the Mechanistic-Empirical Pavement Design Guide (MEPDG) software, the authors assessed the implications of truck positioning on flexible pavement performance and design, and then quantified both the negative and positive effects of autonomous trucks according to the two main pavement surface structural failure criteria – fatigue cracking and rut formation.

The model pavement used to predict the critical strain responses consists of 15cm of asphalt concrete, 20cm of aggregate based (modulus of 250kPa) and AASHTO A-4 subgrade, i.e., modulus of 50kPa (Noorvand et al., 2017).

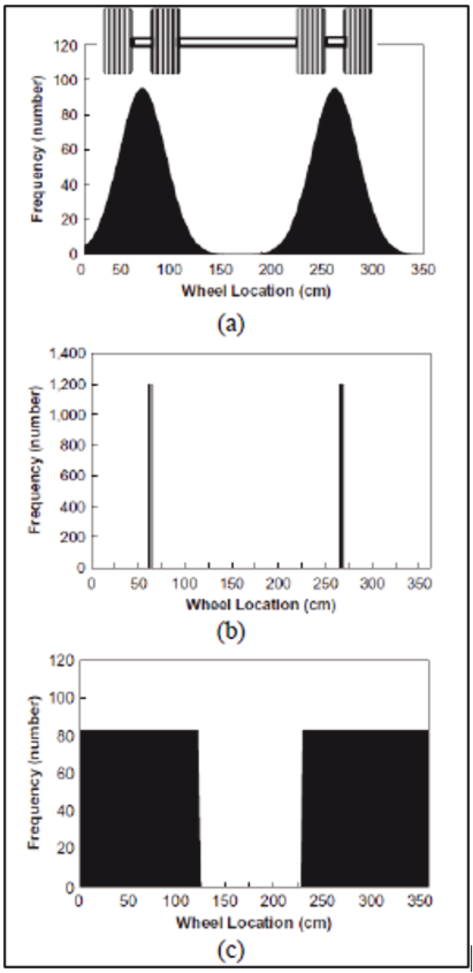
Using a mean edge of tyre location of 37.5cm from the lane marking and a standard deviation of 25cm, the lateral positions of the human-driven trucks were based on a normal distribution model according to the equation:

$$f(x;\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad \text{Equation 4-1}$$

Where;
σ = standard deviation (wander effect),
μ = center of actual wheel, and
x = variable locations of tires.

The equation essentially represents the probabilistic modelling of wheel wander on the basis that vehicles are centred on the lane with a level of uncertainty. Wheel wander is modelled using a zero mean normal distribution with a known standard deviation. The value used for a standard deviation dictates the level of randomness of wheel wander.

The autonomous vehicles on the other hand were modelled as either zero wander (closely restricted) or as uniformly distribution (using the whole lane width but constrained within the 360cm lane width). Figure 4-1 shows the three different distribution models used in the simulation analysis.



(a) normally distributed manual trucks

(b) zero wander of CATs,

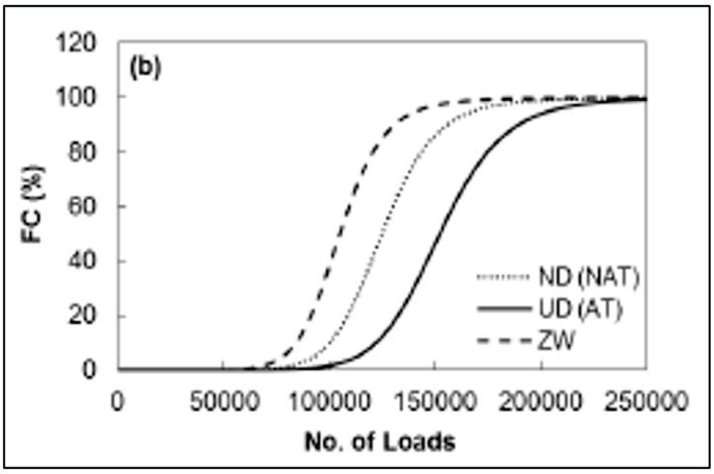
(c) uniformly distributed trucks

Figure 4-1 Wheel position probability distribution (Noorvand et al., 2017).

The analysis used 3 different operational scenarios: status quo (0% CATs), shared CATs/non-CATs lanes, and segregated lanes for CATs. The authors compared the effect of the different lateral control scenarios and the pavement thicknesses. The study then used the results from the simulation to balance implementing wider, thinner pavements against narrower, thicker pavement.

4.1.1.2 Results of pioneering research into CAVs impact on pavement performances

The study found that compared to manual vehicles on a typical flexible pavement (moduli of 2500 kPa), AV uniform wander delayed the onset of critical fatigue cracking (i.e., when pavement reaches 20% of cracking) by a factor of 0.81. For zero wander (precise wheel tracking), critical fatigue cracking was hastened by a factor of 1.18. The data from the fatigue cracking analysis is presented in Figure 4-2. A similar trend was observed for rutting failure. The stresses generated by uniform distribution of AVs was found to be 0.65 of that for manual vehicles, while the zero-wander case more than doubled the stresses to a factor of 2.2, implying that rut depressions caused by zero wander was the deepest, followed by normally distributed manual trucks. Uniform distribution wander caused the least deformation depths in the pavements. The rutting results are presented in Figure 4-3.



ND = normal distribution, UD = uniform distribution and ZW = zero wander

Figure 4-2 Fatigue cracking (Noorvand et al., 2017)

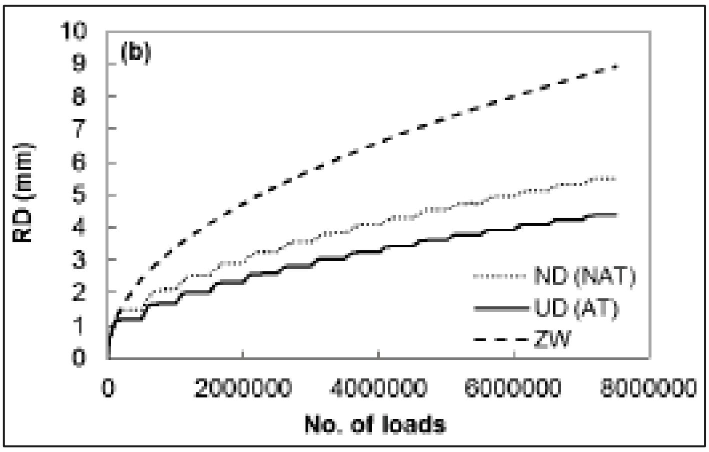


Figure 4-3 Distributions and rut depths (Noorvand et al., 2017)

Another key finding of this study was that the designed thickness and initial construction cost for all evaluated cases (different combinations of autonomous and non-autonomous trucks) of segregated and integrated scenarios suggest the beneficial deployment of segregated scenario over integrated scenario both at higher percentage and lower percentage of autonomous trucks incorporation. While the maximum reduction of thickness for segregated scenario was achieved with 70% of uniformly distributed autonomous trucks, such reduction was obtained with 90% of uniformly distributed autonomous trucks for integrated case. For the lower percentages of autonomous trucks, the cases of segregated scenario in general showed lower construction cost than those of the integrated scenario. In the absence of appropriate control, specifically by repeatedly positioning trucks in the same location, the amount of damage could be highly detrimental, and noticeable influences may occur at autonomous truck volumes as low as 10%. Essentially, the study concluded that segregation should be adopted.

The overarching conclusion from ASU investigation was that, if controlled appropriately, autonomous trucks could be highly beneficial for the pavement infrastructure design, and they would be most effective when they represented more than 50% of the total truck traffic.

4.1.1.3 Limitations of the ground-breaking pavement-CAVs research

As a first real attempt at performing technical analysis on pavement failure under different CAV wheel wander loading, the ASU paper contained some very insightful methods for comparing the effect of lateral truck locations on pavement failure and design. This notwithstanding, there are several limitations and omissions which provide opportunity for further work.

Firstly, one of the sub-scenarios under the segregated CATs/non-CATs scenario was that 2 lanes would be CATs only, under high penetration rates of CATs. This would require non-CATs to share a lane with lighter traffic. This paper, however, did not analyse how this could affect traffic, as trucks are slower, and will cause cars to slow down, thereby negatively impacting on traffic flow efficiency, fuel consumption, travel times and delays.

Also, other truck-related parameters, such as differences in weight, acceleration rate, and operational speed of autonomous trucks versus non-autonomous trucks were not accounted for in the study. In all cases, performance was estimated with respect to rutting, fatigue cracking, and overall pavement smoothness, and the results were compiled in terms of reduced pavement thickness.

Crucially, the investigation by ASU retained many of the salient features of current roadway infrastructure intact (e.g., fixed lanes delineated by markings, uniform cross sections within lanes, uniform materials across the entire lane width, and so forth) and thus did not challenge the established design paradigms. The publication then identified that further study was required to develop wholly new pavement and roadway designs that took optimal advantage of autonomous technologies. For instance, the impact of reduced or increased lane width on stresses.

The lateral wandering of trucks to increase pavement life will reduce the fuel efficiency benefits of platoons. It is likely to be more complicated to programme for this wandering and may be disconcerting to manual vehicle drivers. Finally, ASU's method does not provide the flexibility that would allow the effect of changes to axle load lateral position, axle widths and lanes to be measured.

4.1.2 Application of statistical distribution modelling

4.1.2.1 Utilising probability distribution functions to predict lateral position of autonomous vehicles wheel loads

This sub-section examines some of the important work carried out to analyse pavement structural response when subjected to CAV wheel loads, where the load positions were predicted by probability distribution theories.

4.1.2.1.1 Exploring the effects of wheel standard deviations from centre of traffic lane

In a US-based research collaboration to build on the ASU work, Texas A&M Transportation Institute (TTI) teamed up with Texas A&M University (TAMU) (Zhou et al., 2019a), and then with San Diego State University and Virginia Tech Transportation Institute (Zhou et al., 2019b). The two works introduce normal distribution wandering patterns for AVs, but with markedly different standard deviations from the normal distribution model of manual trucks. AVs were taken to have a standard deviation for the lateral traffic wander pattern at least three times smaller than human driven vehicles.

The TTI/TAMU study used a typical pavement structure (shown in Figure 4-4) carrying 30 million equivalent single axle loads (ESALs) within a 20-year design period. The typical pavement structure was subjected to two scenarios: 100 percent human-driven truck traffic and 100 percent AV truck traffic. These scenarios were simulated by the Texas Mechanistic-Empirical pavement design and analysis program (TxME), a bespoke program that models pavement structural response to different wheel wander modes and lateral standard deviations.

TxME computes pavement responses to loadings using sophisticated fracture mechanics, finite element analysis, and elastic layer computer models. Accumulated damage is determined from an incremental damage approach, divided into 1-month time periods. Damage over time is then related to pre-selected pavement distress thresholds (Hu et al., 2013). Figure 4-7 illustrates the TxME software input interface.

For human-driven traffic, the wander was assumed to be normally distributed with a standard deviation of 250 mm (10 in.). AVs were modelled based on either a 75mm standard deviation for close tracking, or uniform wander. A diagrammatic representation of the 3 wander modes is contained in Figure 4-5. The standard deviation for AV lateral wander was based on lane keeping data collected from autonomous driving at a constant speed of 20 mph along a 1-mile long, 42m wide, multi-lane straight road at the test site which was located at the Texas A&M RELLIS campus. See Figure 4-6 for the AV lateral wander test site.

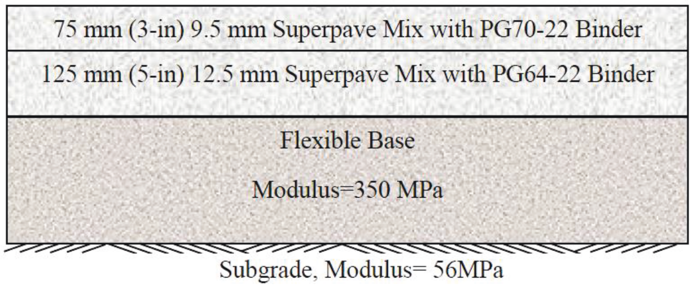


Figure 4-4 Pavement structure used in design analysis (Zhou et al., 2019a)

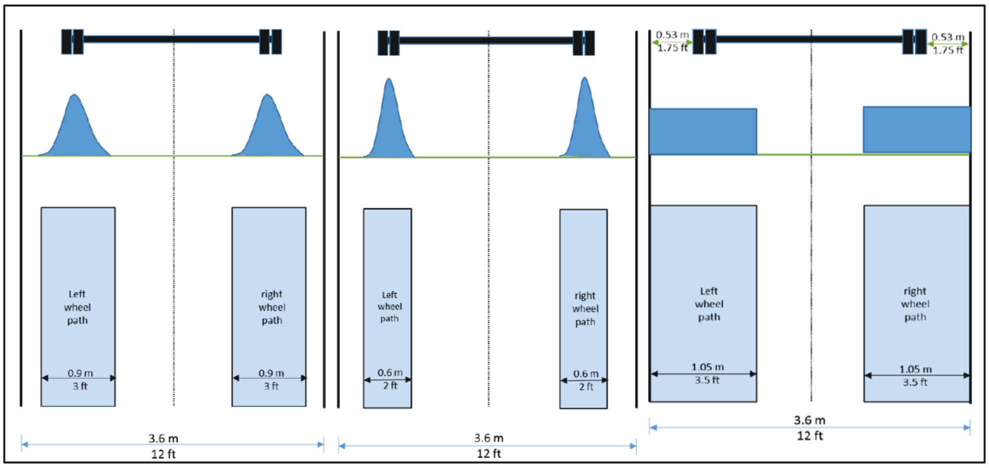


Figure 4-5 Human and AV wander patterns (Zhou et al., 2019a)

Figure 4-6 Site of experiment. Inferred from Zhou et al. (2019a)

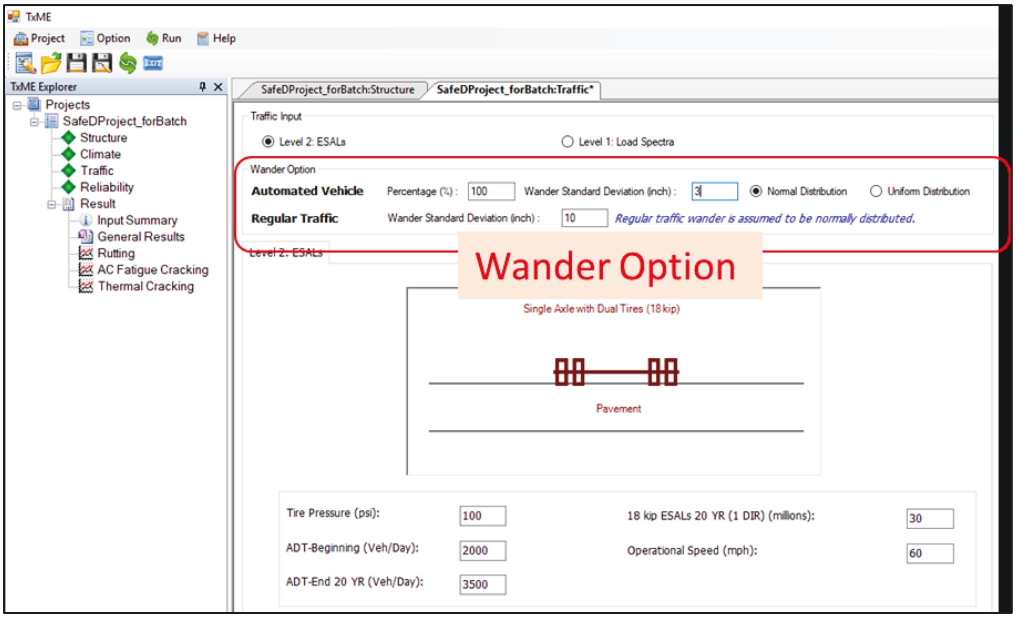


Figure 4-7 TxME software interface (Zhou et al., 2019a)

This work corroborated the 2017 ASU study findings that CAT reduced lateral wheel deviations leads to premature onset of critical pavement structural failure, finding that AVs shortened pavement life by up to 20% percent. Conversely, it concluded at uniformly distributed lateral wandering pattern for AVs would prolong pavement life by 15%.

The findings of this work provided evidence that the autonomous trucks' lateral distribution has a significant effect on highway pavement infrastructure. This presents a basis for instituting suitable vehicle control programming for autonomous vehicles accordingly, although this introduces another challenge of making this more sophisticated control method work.

4.1.2.1.2 Limitations of probability distribution functional modelling of wheel lateral position

Despite its high theoretical value, the studies by TTI and its partners had a few omissions that render it inapplicable as a generalised pavement design approach for CAVs. Firstly, the data used to derive the AV wander were taken along a 1-mile straight road section, 42m wide. But real roads are hardly ever straight, and carriageways seldom exceed 14m in width. AV wander behaviour is likely to be different under realistic public road conditions. Also, the vehicles used to measure AV lateral wander was the Texas A&M University's AV, but its features are not representative of trucks for pavement design. In addition, the speed of the test vehicle was at 20 mph, much lower than the 60mph speed limit for HGVs on motorways. The TxME model uses a more realistic operational speed of 60mph in the analysis – see Figure 4-7 above. These higher speeds could impact on the tracking accuracy, and therefore, vehicle wander of AVs.

The study examined and recommended uniform distribution of AV lateral position, a wandering functionality in autonomous vehicles such that the entire traffic lane is occupied. That way, the stresses are distributed over a wider area, delaying the onset of both fatigue cracking and rutting failures. However, vehicles occupying full width of lanes are likely to discourage manual vehicles from overtaking in adjacent lanes, similar to cars being reluctant to drive next to - or overtake - HGVs in narrow lanes, see Figure 4-8 (Nassrullah and Yousif, 2019). This will have disbenefits for traffic flows. The phenomenon of driver shyness might also imply that occupants of an autonomous vehicle uniformly distributing its wheel loads would feel uneasy and some level of discomfort.

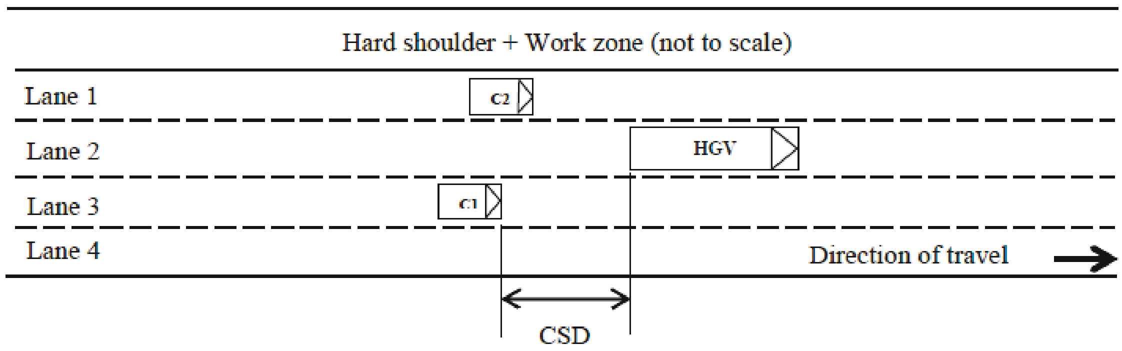


Figure 4-8 Lane width and Clear Space Distance (CSD) (Nassrullah and Yousif, 2019)

Crucially, the study focussed only on pavement aspects of highways, and did not include a holistic review of the impact of the various scenarios on construction and maintenance costs, accidents, traffic flow parameters such as delays, queuing, congestion, journey times, effects of proximity of traffic streams, etc. Finally, the study used a 3D-finite element analysis software TxME to undertake the assessment, and field study to validate the data should be sort.

These relatively recent studies analysed the impact of various CAVs wander modes and CAV penetration rates on pavement deterioration, concluding, mainly, that the increased tracking accuracy of CATs can lead to premature pavement failure, but that uniform wheel wander could be used to minimise channelisation, hence improving the longevity of pavements. These studies also found significant pavement performance differences based on CATs-to-manual trucks ratios. They found that increasing the proportion of CATs, while operating uniform wander, reduced fatigue pavement failure, while zero wander significantly led to early onset of structural pavement failure.

4.1.2.2 Expanding wheel load lateral distribution mode alternatives for autonomous vehicles

In this section, a critical review is undertaken to investigate existing research where software, which is based on the multi-layered soil theory of pavement analysis, has been used to calculate impacts on the CAV wheel loading through pavement structure.

4.1.2.2.1 Background to the application of the finite element method

Further work has also been undertaken using finite element analysis (FEA) techniques to compare pavement deformation and fatigue failure for different AV lateral distribution modes, and to develop lateral positioning control schemes (Chen et al., 2020b, Chen et al., 2020a, Chen et al., 2019).

The FEA approach is a computational method used to simulate the behaviour of asphalt pavement layers under various loading and environmental conditions, enabling stresses, strains and deformations at any point in the pavement structure to be isolated and analysed.

4.1.2.2.2 Exploring lateral control distribution modes

The FEA technique enabled an expansion of the lateral distribution of the autonomous trucks to four different modes: zero-wander, uniform distribution, double peak Gaussian mode, and two-section uniform mode. These were in addition to the normal distribution model that manual trucks followed.

The uniform distribution, double peak Gaussian mode and two-section uniform mode all produced better pavement performance compared with the normally distributed manual trucks, with the two-section uniform distribution of autonomous trucks producing the best pavement performance, prolonging the pavement life by 2.3 years (40%), and reducing fatigue damage by up to 35%. When the proportion of autonomous trucks is over 50%, the deployment of the two-section uniform distribution resulted in a significant decrease in rutting depth by delaying the maintenance year by 2.3 years.

Interestingly, at higher penetration rates of AV (50% and above), the pavement durability for two-section distribution was not sensitive to changes in proportion of AV to manual trucks. On the contrary, under the zero-wander mode, the pavement experienced extremely concentrated distribution of wheel tracks, leading to the onset of the critical rutting depth being reached 1.56 years sooner under 100% AV. Premature pavement failure worsened with increasing proportion of AVs with zero wander.

Simulations of stress diffusion showed that zero wander trucks produced the worse results - fatigue damage was 2.7 times that of the all human-driven trucks condition, see Table 4-1. This damage worsened with increasing proportion of AVs. For the other three lateral control modes, the higher the proportion of autonomous trucks, the smaller the fatigue damage, which means a positive effect in prolonging the service life of pavements. The modelling showed that the optimal section width of the two-section uniform distribution was 280 mm. The two-section uniform distribution produced the most reduction in fatigue damage of 35%, while the double peak Gaussian mode produced a maximum reduction of 10%.

The double-peak Gaussian distribution model only showed positive results with very high proportion of AVs. The uniformly distributed mode ranks between the two-peak Gaussian and two-section, with a 36% increase to pavement life. Chen et al. (2019).

Table 4-1 Maximum fatigue damage within lane Chen et al. (2019).

Mode	Fatigue Damage	Vehicle Proportion				
		100 + 0	75 + 25	50 + 50	25 + 75	0 + 100
Mode0	DL(10^{-3})	4.945	6.139	8.148	10.19	12.18
Mode1	DL(10^{-3})	4.945	4.666	4.387	4.107	3.830
Mode2	DL(10^{-3})	4.945	4.810	4.675	4.541	4.406
Mode3	DL(10^{-3})	4.945	4.303	3.675	3.298	3.191

Mode0 = Zero wander; Mode1 = uniform wander; Mode2 = Double-peak Gaussian wander; Mode3 = Two-section uniform wander

4.1.2.2.3 Finite element analysis approach to wheel load-induced stress-strain propagation through pavement structure

Researchers used ABAQUS, a 2-D proprietary FEA software to explore the relationship between the number of standard axial loads and rutting deformation. Pavement equivalency theory was used to convert dynamic wheel loads to static loads, due to limitations within the software.

The FEA studies used physical and practical driving constraints (such as safety margins from lanes), statistical probability distribution functions, complex vehicle trajectory predictions and controls methods consisting of advanced trigonometry, and wheel path algorithms, to select a path for subsequent vehicles to follow. See Figure 4-9, which is based on a 3.75m wide lane bounded by white lane lines being 150mm, resulting in 3.6m side effective lane width, the green line denotes the centreline, while μ is the symmetry axis of the normal distribution, sp, ep (marked by the red lines) are the boundaries of dual-wheel geometrically related to axle length (2L), tyre width (r), and safety offset (a) (Chen et al., 2020b).

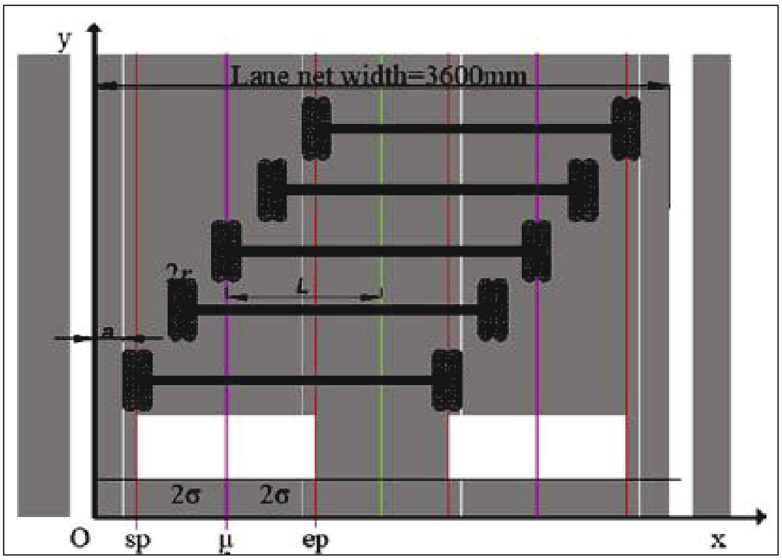


Figure 4-9 Truck wheel route constraints and probability models (Chen et al., 2020b)

The model of the pavement structural layers used in the analysis is shown in Figure 4-10. It consists of 40mm of Stone mastic asphalt (SMA) surface course, 140mm of asphalt concrete base course (made up of 60mm of AC-20 grade bitumen and 80mm of AC-25 bitumen), and 360mm of cement stabilised macadam roadbase. The foundation was made of 200mm of lime-fly ash stabilised soil.

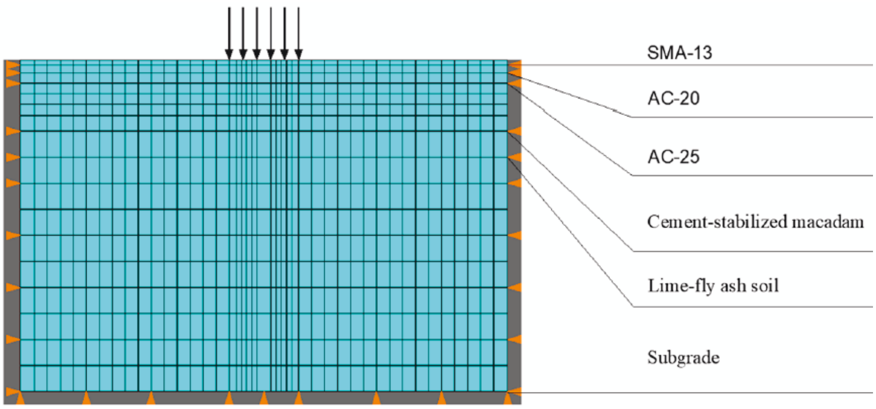


Figure 4-10 Asphalt structure for FEM. Taken from Chen et al. (2019).

The lane wandering constraints of autonomous trucks were based on the centre of the truck's left dual wheel being between 410mm and 1270mm from the left lane marking. This was the distance to prevent encroachment outside the lane. This distance was dynamically altered for the studies. With the four lateral control modes, the distribution of wheel tracks can be dynamically adjusted. The two-section distribution was based on the maximum standard deviation and coefficient of variation.

Three of the four lateral control modes (Mode1, Mode2 and Mode3) followed the probability density functions the vehicle trajectory method using these the below distribution models:

$$Mode1 \ : Probability(x_{TP} = \mathrm{x}) = g_1(x) \sim Norm(\mu, \sigma)$$ Equation 4-2

$$Mode2 \ : Probability(x_{TP} = \mathrm{x}) = g_2(x) \sim Unif(sp, ep)$$ Equation 4-3

$$Mode3 \ : Probability(x_{TP} = \mathrm{x}) = g_3(x) = 1$$ Equation 4-4

Mode4 had no fixed lateral distribution model. Instead, the lateral position was varied in order to minimise the pavement damage experienced within the pavement structure, with the location of the wheels varied to avoid the worse fatigue-damaged sections within the lane. Fatigue damage data was collected and analysed through the use of embedded sensors.

The researchers simulated a vehicle arriving at a sensor area, where its load, lateral position and axle length is captured and sent to the recording system. The system then calculates a target lateral position that minimises pavement damage, based on previous damage across the pavement section. The lateral positions of human-driven vehicles are distributed normally, while the autonomous vehicles distributed according to the four possible modes previously discussed in (Chen et al., 2019). The framework of the lateral control scheme is presented in Figure 4-11, and a layout of the simulated trajectory is presented in Figure 4-12.

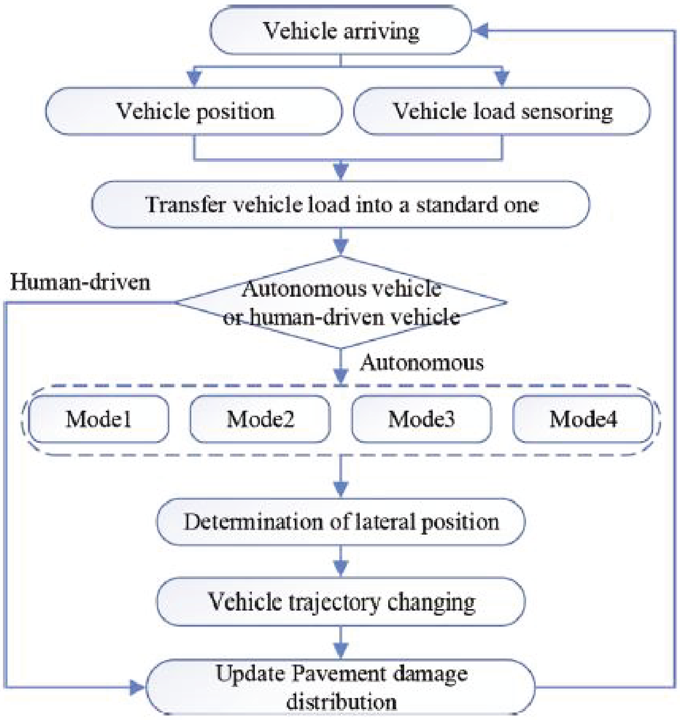


Figure 4-11 Vehicle trajectory framework flowchart (Chen et al., 2020b)

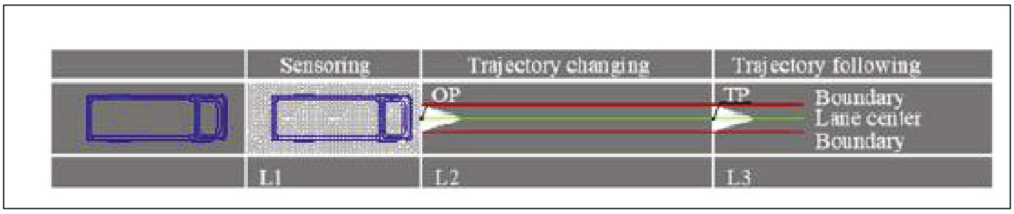


Figure 4-12 Stages of vehicle trajectory simulation. From Chen et al. (2020b).

The fatigue damage method used empirical formulae to estimate the pavement damage, and then assign vehicles to lateral positions that prolonged pavement life.

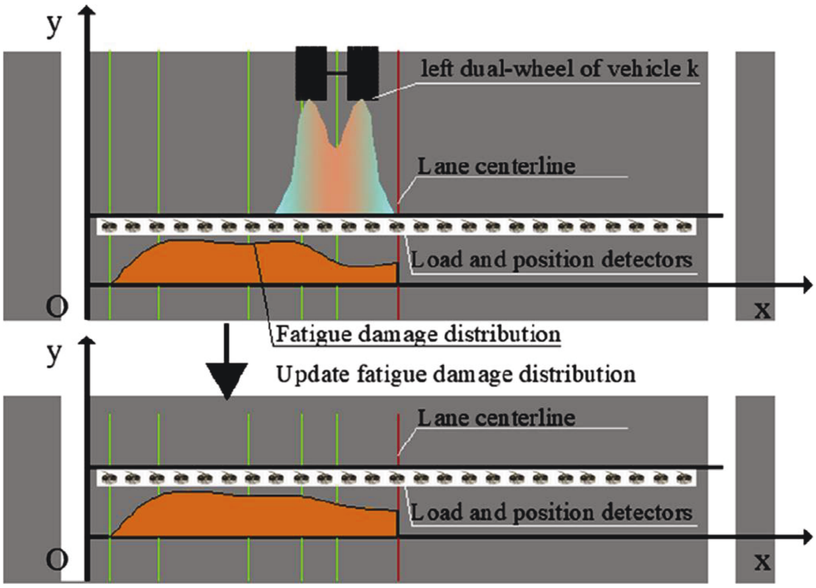


Figure 4-13 Fatigue-based, lateral position assignment system (Chen et al., 2020b)

4.1.2.2.4 Results of finite element analysis for multiple wheel lateral distribution options

The result of the simulation is shown in Table 4-2, and indicates that fatigue-oriented control provides the best performance for pavement longevity. Values in brackets represent change with respect to normally distributed all-manual driving.

The fatigue control method produces a much greater benefit to the pavement at lower penetration of CAVs, for example, at 20% penetration, fatigue damage for the fatigue control method is 1.357×10^{-14}, representing 20% less damage than vehicle trajectory mode under normal distribution (1.698×10^{-14}). Fatigue damage for vehicle trajectory mode at this penetration rate is 5% better than under normal distribution. However, at 100% CAVs penetration, fatigue damage mode and vehicle trajectory: uniform mode are 28% and 27% better than normal distribution, respectively.

One the other hand, lane centring for an all-CAVs traffic results in a 140% increase in fatigue damage propagation. The distribution of fatigue damage plots is shown in Figure 4-14.

Table 4-2 Fatigue damage and probability distributions. From Chen et al. (2020b)

Pro_AVs	Mode1	Mode2	Mode3	Mode4
0%	1.692E-14 (0.00)	1.709E-14 (0.01)	1.701E-14 (0.01)	1.705E-14 (0.01)
20%	1.698E-14 (0.00)	1.605E-14 (-0.05)	1.991E-14 (0.18)	1.357E-14 (-0.20)
40%	1.709E-14 (0.01)	1.507E-14 (-0.11)	2.505E-14 (0.48)	1.282E-14 (-0.24)
60%	1.691E-14 (0.00)	1.411E-14 (-0.17)	3.024E-14 (0.79)	1.251E-14 (-0.26)
80%	1.694E-14 (0.00)	1.331E-14 (-0.21)	3.539E-14 (1.09)	1.240E-14 (-0.27)
100%	1.708E-14 (0.01)	1.233E-14 (-0.27)	4.056E-14 (1.40)	1.224E-14 (-0.28)

Note: The value in the bracket is the increment with respect to the result of Mode1-0%, red color means a positive effect.

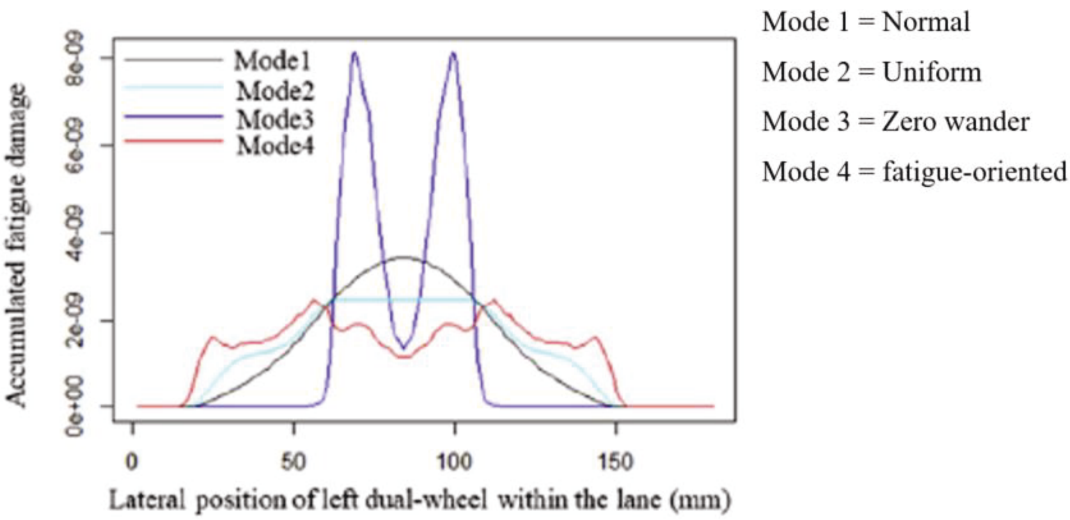


Figure 4-14 Vehicle route and fatigue damage for 100% CAVs (Chen et al., 2020b).

4.1.2.2.5 Conclusions and limitations of the FEA-based studies on CAV pavement performance

Based on the results, the researchers argued it would be uneconomical to design roads specifically for AVs, instead that the ability to choose a more benign control mode such that pavement life is prolonged, should be adopted. However, current technology does not yet allow for the option to vary control from zero/near zero wander to uniform wander. Hence this recommendation assumes that technology for CATs will progress beyond their current capabilities.

One assumption made in this analysis is that the presence of AVs will not affect the lateral position of human-driven trucks, but the effect of this assumption needs to be studied further, as it is possible that the pavement performance benefits of uniform lateral position models of AVs could be negated by worsened operational performance caused by close proximity of AVs to human-driven trucks.

The FEA models incorporated a safety offset of the wheel from the lane line, whereas generally, research papers adopt models that permit straying beyond the lane lines, particularly for manual vehicles.

4.1.2.3 Fixed-path effects on pavement

University of Hawaii at Manoa-led study that also employed FE modelling techniques to measure stress-strain development within the pavement structure, concluded that the fatigue life of pavements could be reduced by as much as 34.5%. (Beheshti Shirazi et al., 2024).

The study, however, did not use variable wander, instead only observing the effects of zero wander, where the wheels travelled a strictly defined path such as for train tracks. This meant there was no opportunity to compare other non-zero wander alternatives.

4.1.2.4 Recovery time effects

For this section, the focus of the review is on studies where the impact of close vehicle following (such as in platooning) is investigated to determine how reduced recovery times of visco-elastic asphalt material affects its durability.

4.1.2.4.1 Underlying phenomenon for reduced self-healing time within asphalt under CAV loading

Other researchers expanded on the pavement analysis to include the effects of reduced vehicle headways that will become a feature of Connected Autonomous Trucks (CATs) platooning (Gungor and Al-Qadi, 2020a, Gungor and Al-Qadi, 2020b). The premise for including this feature was that the reduced headway reduced the recovery time for pavements between wheel loads, which hinders the self-healing of asphalt concrete (AC), and consequently reducing pavement service life. This could accelerate pavement damage accumulation, as the time between two consecutive truck loads will be shorter because of reduced inter-vehicle distance in platoons. The effects of this specific reduced headway phenomenon on pavement life are in addition to the zero wander or channelisation effects discussed in Section 4.1.1 above. In particular, a European Commission-funded study investigated the effects of platoon on asphalt pavements, finding that larger intra-platoon, inter-truck time gaps significantly reduced the strains experienced within the pavement structure, thus benefiting the whole-life cost by reducing maintenance (Leiva-Padilla et al., 2023).

The work on pavement recovery also investigated the impact of using self-driving and communication technologies to control the lateral position of CATs to reduce the rate of pavement failure. Unlike the previous approaches, the pavement recovery analysis used a more discrete division of the normal distribution curve for manual vehicle lateral position, splitting the curve into five equal 20% quintiles.

4.1.2.4.2 Study design and execution

The research on pavement recovery subjected to CAV loading uses a case study to present and quantify a framework called ‘Wander 2D’, that allows the lateral position of vehicle loading to be incorporated into pavement design as an explicit input with any level of randomness which enables it to simulate mixed traffic conditions where human-driven and CATs are travelling over the pavement structures. This improved on the hitherto non-deterministic lateral position of wheel loads which was implicitly included in pavement analysis as a randomised average, despite being an important variable in flexible pavement design.

The resulting framework was applied on the Mechanistic-Empirical Pavement Design Guideline (MEPDG), a widely accepted approach used extensively by pavement design specialists. MEPDG’s damage accumulation equations (i.e., rutting and fatigue cracking) were re-modelled with curve fitting and function approximation techniques by generating a continuous damage profile.

Additionally, lane and axle widths were incorporated in the analysis. The researchers developed a bespoke 3-D advanced pavement FEM model which allowed accurate predictions of tyre-pavement interactions and behaviour of multi-layered elastic material properties (Gungor and Al-Qadi, 2020b). The team applied their newly developed Wander 2D framework to optimise the lateral positions of trucks, leading to a follow-up research paper (Gungor and Al-Qadi, 2020a).

The recovery time work studied the impact of having a centralised system that controls vehicle lateral positions. This study introduced a centralized control strategy which allows the conversion of pavement challenges related to platooning into opportunities.

To optimise the position of the platoons shown in the Figure below, two variables need to be explicitly input into a simulation: the lateral position of each platoon and the reduced resting time due to smaller headway.

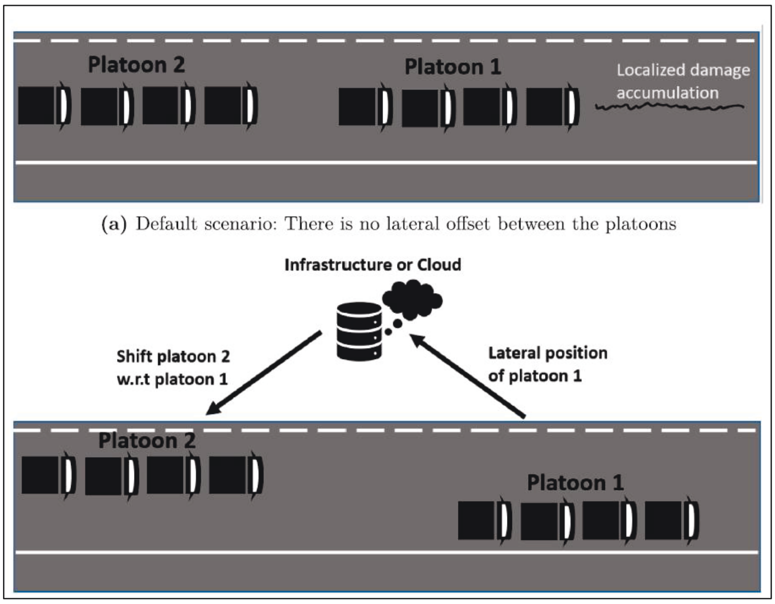


Figure 4-15 V2I optimisation scenarios (Gungor and Al-Qadi, 2020a)

Since no pavement design guides account for these variables (at least at the time of this study), the Wander 2D frameworks was introduced. This modified the conventional mechanistic-empirical design to include truck lateral positions and vehicle distances. An FEM software ABAQUS is then used to calculate pavement structural responses, which are then linked to pavement damage through empirical transfer functions. The asphalt concrete (AC) was modelled as linear viscoelastic and simulated using Prony coefficients, using thick (300mm AC on 300mm bases) and thin (125mm AC on 150mm base) pavement structures. These were supported by a 69MPa subgrade.

The tyre-loading was simulated to exert 3D longitudinal and transverse contact forces through a fine or course mesh within wheel zones, transition zones or at model boundaries. Figure 4-16 illustrates the model developed in ABAQUS.

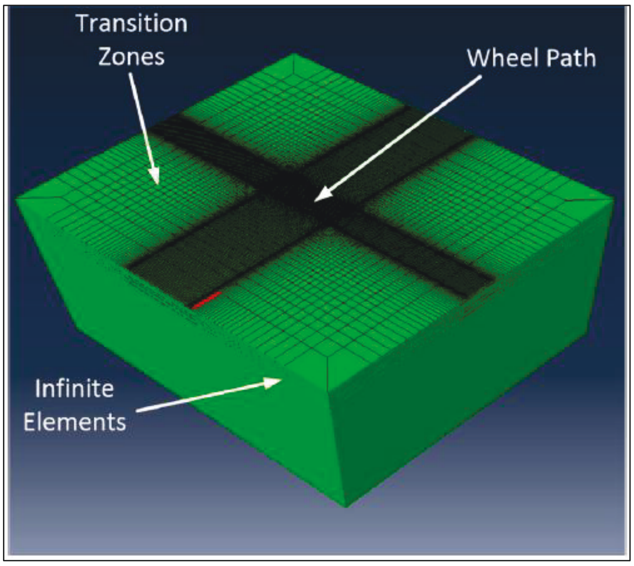


Figure 4-16 3D FEA ABAQUS model. From Gungor and Al-Qadi (2020b)

The objective of optimization is maximizing the pavement service life by manipulating the lateral position of truck platoons (Son and Al-Qadi, 2014).

4.1.2.4.3 Analyses of outputs from pavement recovery time impacts and study limitations

Life cycle cost (LCC) was found to reduce by 50% compared to channelised traffic, from the perspective of the Overseeing Organisation (Road Agency). However, the operational (or user) costs are significantly more for the optimised control, see Figure 4-17. Therefore, this paper's results are only partially optimised as it does not incorporate operational costs.

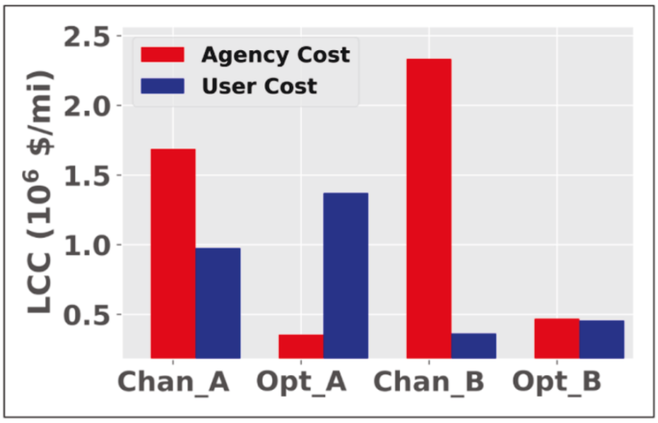
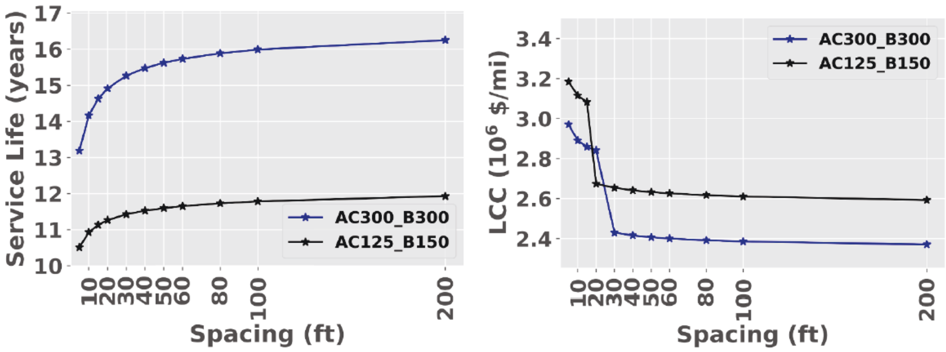


Figure 4-17 LCC by pavement type and modes (Gungor and Al-Qadi, 2020a)

Further analysis was performed to show how inter-vehicle spacing, which affects the resting time of pavements, impacts the pavement service life, and therefore, LCC. The results are shown in Figure 4-18 below and indicate that shorter inter-vehicle spacing leads to a more rapid pavement deterioration. This, therefore, increases the LCC. However, this result is incomplete as there is an operational compromise: increasing the vehicle spacing means the full benefits of reduced fuel consumption from aerodynamic streamlining cannot be realised.



(a) Spacing vs Service Life (SL) (b) Spacing vs Life Cycle Cost (LCC)

Figure 4-18 Truck space impact on pavement and LCC (Gungor and Al-Qadi, 2020a)

A further limitation of this study was that only standard lane widths were used in the analysis (12ft or 3.6m). Moreover, no analysis of the impact of neighbouring lanes was carried out (wandering could impact on driver behaviour due to driver shyness). The sole consideration was movements within a specific lane.

Furthermore, although life cycle cost analysis (LCCA) was calculated, this was done to quantify the optimised lateral position from the centralised control system, to minimise pavement damage. Other aspects of the LCCA such as initial conversion cost, were not included as decision variables in the optimisation.

4.2 Road geometrics

4.2.1 Exploratory geometry investigations

Consultants Hanson Professional Services carried out one of the earliest reviews of standard highway geometric design elements that are likely to be affected by having an all-CAV traffic. Hanson concluded that Stopping Sight Distances (SSD) values for autonomous vehicles would be highly sensitivity to perception reaction times. General commentary is then included on the effects on cross-sectional items, including lane widths, hard shoulders and object set-backs (McDonald, 2017).

A 2018 SunCam online transportation engineering course material also then presented a high-level, unquantified and an un-detailed conceptual overview of how geometric designs will be affected by autonomous vehicles. The information presented therein referenced the impact of vehicle acceleration rates on maximum gradients if vehicle technology developers decide to incorporate fuel efficient acceleration features. A brief conceptual discussion is also included on the differences between ‘machine vision’ or V2X object detection, and ‘human vision’, relating to SSD values (Washburn, 2018a).

The first known study to quantify the impacts of amending geometric design models evaluated traditional vehicle visibility models, which were then revised to capture the effect of autonomous vehicles on highway design elements. This was achieved by using a modified value for perception-reaction times for autonomous vehicles of 0.5s (compared to the AASHTO value of 2.5s). The results of these re-analysed SSDs are reproduced in Figure 4-19, and shows, for instance, that on flat road sections with 120kph speeds, SSD required for autonomous vehicles is 180m, which is 70m shorter than the current AASHTO standard of 250m. In addition, variations to driver’s eye height and the headlight beam properties were used to remodel vertical curves. Again, using a 120kph speed, the rate of vertical curvature (K) values for sag curves reduced from 63 to 4, and then from 95 to 40 for crest curves (Khoury et al., 2019).

This study, however, only based the models and parameters on AASHTO values, with no analysis carried out on UK standards. Another deficit in this work is that it is based on 100% autonomous vehicle fleet. This over-simplifies the analysis as, in reality, there is likely to be co-existence of autonomous and conventional vehicle for some time. Having both sets of vehicles will introduce complexities in selecting geometric parameters that meets universal satisfaction. Finally, when a case study was applied to quantify the effect of the changes, significant savings in earthworks were obtained (excavated and fill material volume savings of 7.67% and 47.22%, respectively). But this comparative cut/fill analysis did not account for potential changes to cross-sectional widths or pavement depths for CAVs, both of which would affect the calculated earthworks volumes.

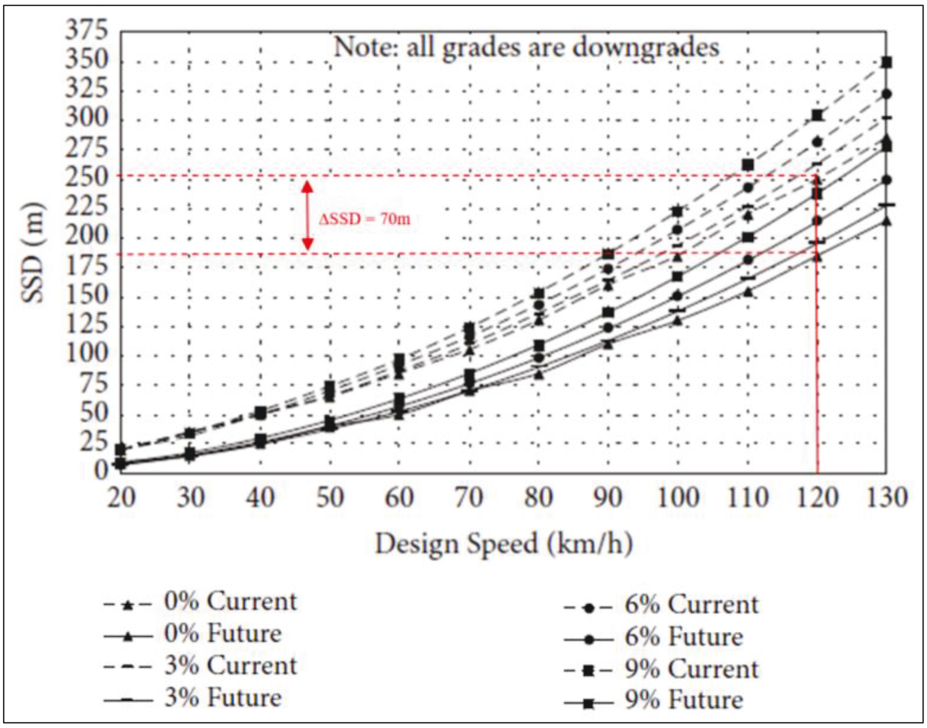


Figure 4-19 Standard and re-calculated SSD. Adapted from Khoury et al. (2019)

4.2.2 Innovative cross-sections

The National Cooperative Highway Research Program (NCHRP) investigated the benefits of various dedicated lane options, concluding that shared dedicated lanes were the most suitable option at lower Market Penetration Rates (MPRs) and exclusive dedicated lanes at mediums MPRs; dedicated lanes were discouraged at high MPRs. However, the geometrical features of the dedicated lane were based on a standard High Occupancy Vehicle Lane, hence opportunities to test the traffic flow impact of modified lane widths to take advantage of CAT narrow tracking or widely spread wheel load was missed in this study, too. Although a range of traffic flow volumes were investigated, these were applied to different case study sites, with each having unique and different geometries, hence other factors could have affected the outcome (National Academies of Sciences and Medicine, 2019).

Furthermore, a study of the motorway system in the Netherlands also researched the impact of using different methods to separate the dedicated CAV lane - as well as the lane position within the carriageway - using driving simulator with test subjects. But this was based on Dutch national road design standards, so lane widths were limited to standard ones. Traffic volume effects were not included in this research, either (Schoenmakers et al., 2021). Similar simulator-based research, also in the Netherlands, only investigated one type of penetration (43% MPR). There was no variation in traffic flow volumes, and the lanes used were standard (Rad et al., 2021).

So, while there have been various studies relating CAVs performance to traffic counts, none provides the level of variability in the scenarios to allow significant statistical conclusions to be drawn from their results.

4.3 Roadworks and temporary traffic management

4.3.1 Understanding the effects of roadworks on traffic

Road maintenance works imply momentary unavailability of traffic lanes, use of narrow lanes or road closures as part of safe traffic management. This can significantly increase driving times for motorist through diversions and detours. Yousif et al. (2017) emphasised the significance of roadworks when concluding that traffic operational turbulence and safety record are impacted by temporary traffic management arrangements incorporating narrow lanes. Narrow lanes cause drivers to reposition their vehicles within the lane, both laterally and longitudinally (Yousif et al., 2017).

This needs to be included in cost models because frequency of maintenance is dependent on pavement deterioration rates.

4.3.2 Scarcity and limitations of current studies investigating autonomous vehicles performance in roadworks situations

There is limited research on impacts of retrofitting current roadworks set-ups in scenarios that include CATs, with the relatively few existing publications being based on heterogenous vehicle operations, rather than segregated CAT lane configuration.

The University of Wyoming used simulation to analyse the safety performance of CATs in specific weather conditions, finding that CAVs are safer at work zones compared to manual vehicles. The study also found that CAVs improved traffic flow through speed harmonization (Adomah et al., 2021). However, the study was based on heterogenous vehicle fleet, rather than segregated lanes.

Other research in this area have focussed on the use of CAVs as part of the temporary traffic management set up to provide safe environments for roadworkers (Tang et al., 2021), hence their findings may not necessarily directly apply to the public motorists.

Yet another category of research regarding CAVs and work zones, mainly provides insight into the technological system requirements for CAV operations (Park et al., 2016).

This group of studies do not address the highway engineering elements associated with roadworks planning and installation, which should be considered during the design phase.

4.4 Limitations in current research

4.4.1 Dominance of traffic flow studies for connected and autonomous vehicles

Despite the potentially significant effects of CAVs on highway infrastructure, most of the available research focuses on traffic flow implications of CAVs (Khoury et al., 2019, Washburn, 2018b, McDonald, 2017, Paulsen, 2018).

This is reinforced by a UK Department for Transport study which conducted a literature review on CAV publications (Atkins Ltd, 2016a). The authors of the report identified 34 publications which were deemed to have made key contributions around CAVs. But the focus of these publications was on traffic flow parameters such as congestion, headways, safety, and capacity. None contained details on the actual engineering aspects such as pavement design and road geometry. To support this further, several studies (Arbib and Seba, 2017, Talebian and Mishra, 2018, Transport Systems Catapult, 2017) have sought to develop methods to forecast market penetration of CAVs.

Moreover, there is a body of research work (Milakis et al., 2017, Shladover et al., 2018) dedicated to predicting motorist attitudes to CAV in the short, medium and long-term. The approaches used in these analyses are generally based on assessing how social, economic, and technological developments would affect CAVs introduction into mainstream road networks.

Furthermore, other research covering detailed technical elements of CAVs (Makridis et al., 2018b, Atkins Ltd, 2016c, Gillam et al., 2018, Kockelman, 2017, Zegers et al., 2018), tend to focus primarily on capacity performance of platoon trucks and/or autonomous vehicles tested under a variety of conditions, especially safety. To the detriment of ‘hard’ highway engineering design elements such as geometry and pavements, the authors of the existing studies concentrate on the ‘soft’ issues of environment, social, road capacity and economics.

4.4.2 Technological infrastructure research and general scarcity of engineering studies

Another well-researched aspect is the beyond-vehicle technologies (such as roadside infrastructure) needed to support connected and autonomous driving. A number of publications (Darbha et al., 2018, Harfouch et al., 2018), provide results of research into platoon based inter-vehicle communications systems.

In addition, specialised research on localisation has examined the use of accurate and effective vehicle position detection technologies suitable for real-life platoon driving deployment (Kuutti et al., 2018).

A thorough review of existing research by Farah et al. (2018) concluded that much of the existing works focus on the impact of automated and connected vehicles on digital infrastructure rather than physical civil engineering infrastructure.

Another recent literature review completed in 2019 as part of a theoretical study into the potential effects of CAVs on highway design confirmed the existence of a knowledge gap. The study identified that there was very limited prior studies investigating the effects of introducing autonomous vehicles on highway geometric design elements (Khoury et al., 2019).

4.4.3 Summary of limitations in existing research

Whereas self-driving vehicles are based on the latest cutting-edge technologies in artificial intelligence with reduced or no human driver input, highway design parameters in use today are based largely on classical civil engineering principles developed several decades ago, with human behaviour being central to many design considerations. This chronological difference complicates efforts to offer holistic studies linking CAVs in pavement and/or geometric designs.

Studies on self-driving and connected vehicles to date have generally been carried out either using current road design standards, or existing roads unlikely to have been built with consideration for CAVs. Methodologies have also largely involved pre-existing tools, which were developed for conventional traffic. Importantly, these studies hardly focus on key physical civil engineering infrastructure such as pavements.

Clearly, there is a dearth of research into the suitability of current road design approaches for the radically different driving regime of CAVs.

The literature review has shown that investigations into relationships between CATs and engineering aspects of road design are scarce. Most of the available research focusses on traffic flow, or on technology and technological infrastructure requirements. The few studies on designing highway infrastructure for self-driving vehicles typically analyse pavements and lane widths separately. This is despite numerous research providing evidence that channelisation and narrow lane usage for manual driving could accelerate pavement damage and impact cross sectional geometry design requirements (Siddharthan et al., 2017, Shafiee et al., 2014, Zhang et al., 2017, Mecheri et al., 2017, McGarvey, 2016). Typically, performance under roadworks conditions are not included in these studies.

Collectively, the sparce pavement-CAVs research analysed the impact of various CAV wander modes and MPRs on flexible asphalt pavement deterioration, concluding that the increased tracking accuracy of CATs can lead to premature pavement failure, but that uniform wheel wander could be used to minimise channelisation, hence improving pavement longevity. These studies found pavement performance variances based on MPRs. Particularly, under high MPR, uniform wander delayed pavement failure, while zero wander caused early failure. Crucially, none of the studies performed a whole life analysis that included both conversion construction and operation costs of using bespoke lane widths.

Studies on lane width requirements for autonomous driving usually only consist of undetailed, high-level reviews. These studies acknowledge that cross-section requirements for autonomous vehicles will be different. So far, there is not yet a quantified analyses on extent of lane width changes that can be applied for CAVs implementation.

Although some previous research on CAVs and work zones showed how autonomous vehicles can improve on safety and traffic flows, the scenarios modelled are not suitable for practical applications for CAVs as part of mainstream transport system.

In summary, the limitations of pavement research to just standard lane widths, and only under normal operations, means that CATs pavement deterioration behaviour for non-standard cross-sections and incorporating roadwork conditions remain, uninvestigated.

4.5 Developing whole-life costing methods to address research gap

By developing non-standard cross-section options, this PhD study will seek to apply the principles of whole-life cost analysis to enable the comparison of different implementation solutions (Tilly, 2011).

To ensure the full life cycle is considered, the process for developing highway projects from planning to maintenance will be applied (Antillon et al., 2018). These include:

- Agency costs, ie, costs incurred by road authorities, and include the initial conversion as well as maintenance/rehabilitation costs)
- Road user costs, including travel time costs, vehicle operation costs (fuel consumption/emissions), and safety/accidents.

These are now detailed in the subsequent Chapters.

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Chapter 5 EVALUATING ROAD DESIGN AND OPERATION OPTIONS FOR CONNECTED AUTONOMOUS VEHICLES USING MULTI-SCENARIO COMPARISONS

5.1 Initial scoping and assessment of technical feasibility

5.1.1 Defining research base case study section

Complex multi-vehicle interactions between autonomous and manual vehicles are still not fully understood (Zhu et al., 2022). So, to preserve the focus of the research on cross-section impacts, a conceptual 3km corridor link was used. As shown in Figure 5-1, a 3km section is the minimum length of link road over which traffic flows will remain stable. This meant junctions, which would have introduced lane-change and weaving maneouvres, were excluded (Department of Transport, 1995). The use of a 3km section that is uninterrupted my junctions enables flows over a link to be modelled, without introducing elements that are currently less determinate, such as how autonomous vehicles will join the motorway at a junction. With this approach, the study can be modelled more accurately to predict autonomous vehicles effects and costs of safety, emissions driving behaviour.

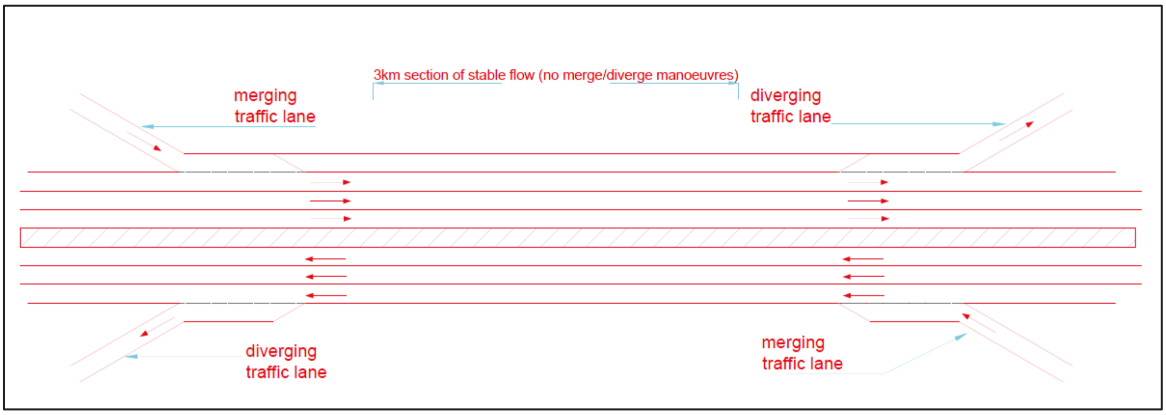

Figure 5-1 Length of stable and predictable traffic flow

Figure 5-2 is a photograph of an actual existing motorway upon which the conceptual section was modelled.

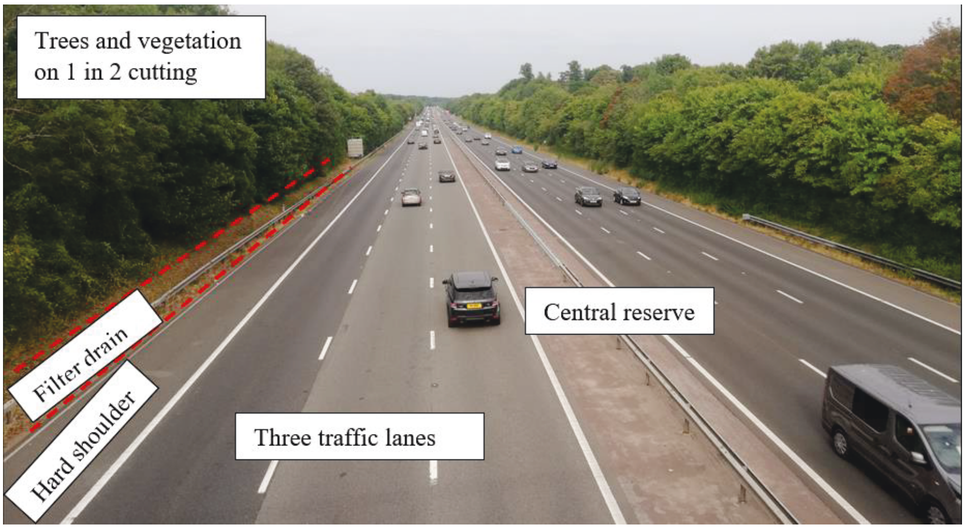

Figure 5-2 Example actual existing motorway with salient features

A section for the conceptual highway used for this research is shown in Figure 5-3. It consists of a 46.1m wide cross-section (between boundary fences) that is laterally symmetrical about the centre of a 4.5m wide central reserve, with three standard traffic lanes 3.65m, 3.7m and 3.65m wide, respectively, and a 3.3m hardshoulder, all complying to current standards (Highways England, 2020a). Next to the hard shoulder is a 2m verge with filter drain and manholes, then a 2m high cutting one a 1-in-2 angle slope face covered with mixed planting. Wooden boundary fences are located at the top of the slope (offset 0.5m for the fence foundations). Beyond the highway boundaries are undeveloped, agricultural third-party lands, populated with mature trees.

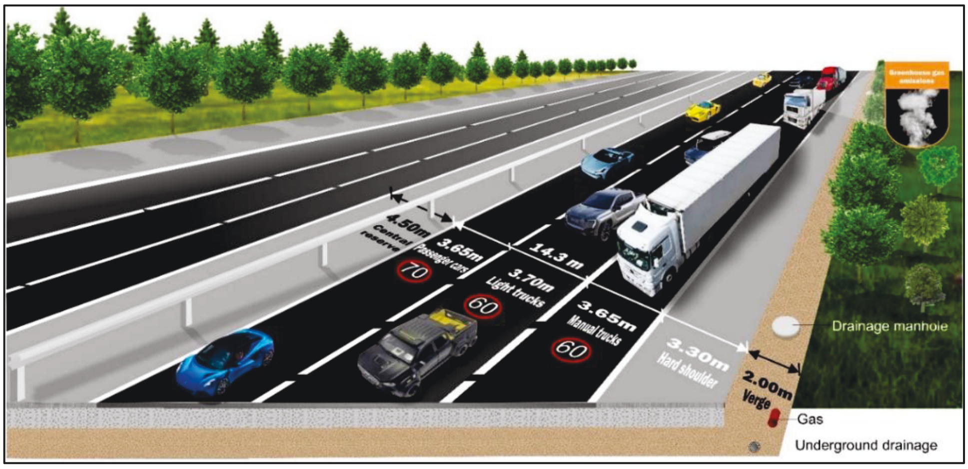

Figure 5-3 Conceptual existing highway modelled on example motorway

5.1.2 Engineering and designing geometric cross-section alternatives

Using the attributes of the conceptual section as base-case, multiple alternative cross-sections were developed. In all alternatives the outer lane (Lane 1) was designated a dedicated CAT lane. A manual truck (MT) lane (Lane 2) was then installed, and then either 1 or 2 Passenger Car (PC) lanes (Lanes 3 and 4), depending on the remaining carriageway width. Although not permitted on motorways by current standards (Highways England, 2020a), the dedicated CAT lane configuration was chosen as it offers the best operational results (National Cooperative Highway Research Program (NCHRP), 2018). Because early CAV adoption is expected to be for heavy trucks (Hummer, 2020), all lighter vehicles (PCs and vans) were analysed as having no or only partial autonomy, and would therefore occupy the manual lanes.

A sample of the investigated cross-section alternatives are shown in Figure 5-4. The lane widths ranged from 2.85m to 5m for CAT, 3m to 4.3m for MT, and 2.5m to 3.65m for PC lane, increasing in 0.5m intervals. These unconventional widths for the CAT lane were based on their special precise wheel tracking capabilities (uniform and zero-wheel wander); the non-standard widths for the MT and PC lanes were derived from existing research on reduced lane widths for motorways (Kondyli et al., 2019), as well as from industry guidance for implementing narrow lanes for temporary traffic management (Gregg, 2007).

The non-standard cross-sections offered the opportunity to test how innovative highway designs could take advantage of – or hinder the benefits from – CAT driving features. The existing paved area was to be maintained; earlier research published as a journal paper during this PhD showed that widening will incur high costs, which could undo the economic benefits of CAT (Jehanfo et al., 2022). Section 5.1.1 above details the features including hard shoulder, verge and land constraints, that would be impacted in implementing widening options.

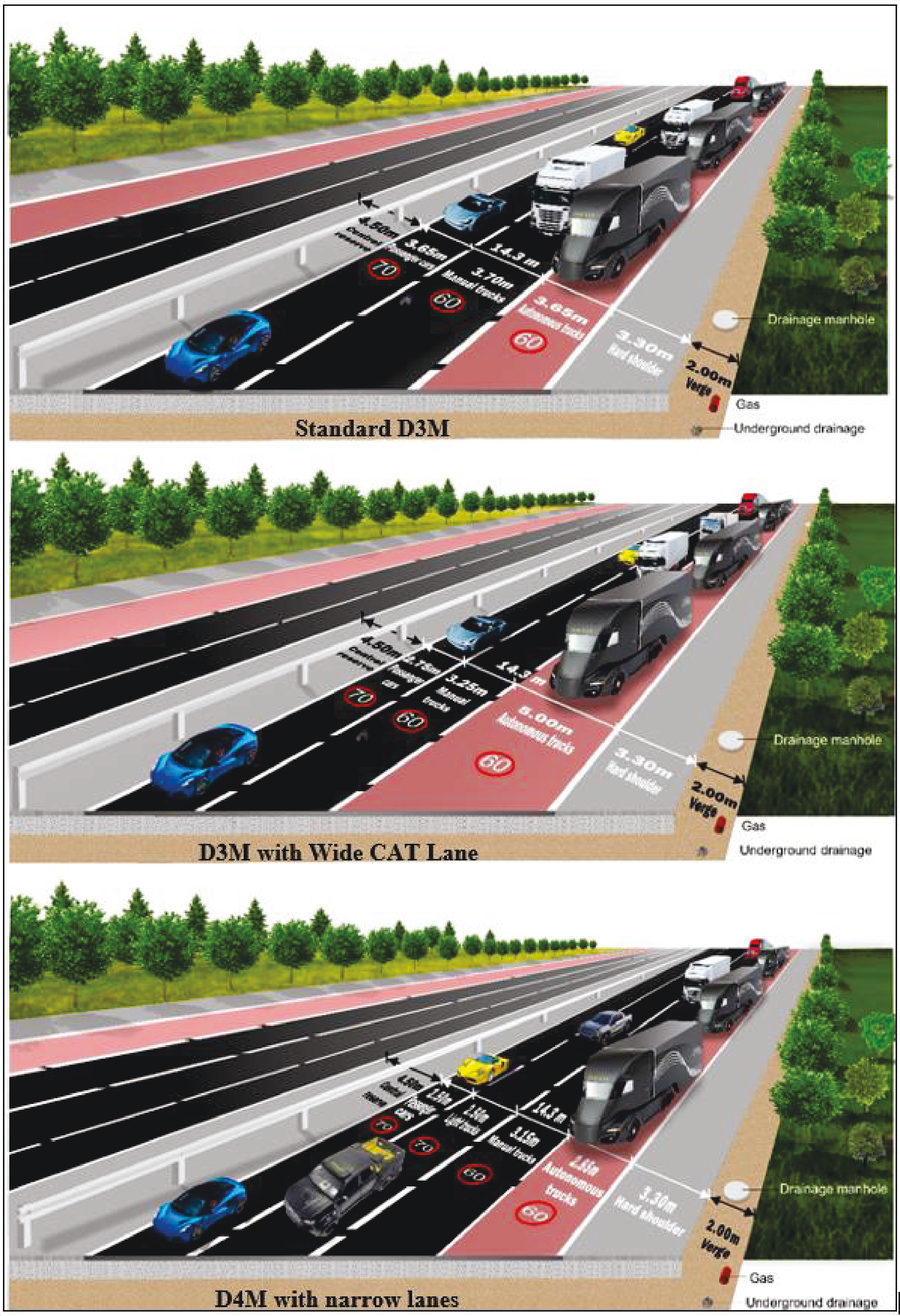

Figure 5-4 Dedicated CAT Lane alternative cross-sections

Broadly, the alternatives used in the research can be categorised in accordance with the following sub-headings. The alternatives are also described therein.

5.1.2.1 Standard D3M

In this option, the Base Case is left unchanged as a standard D3M cross-section, with the outside lane used as a 3.65m wide dedicated CAT lane. All physical features are retained, hence no conversion costs incurred.

This configuration enables an assessment to be made on the impact of implementing autonomous vehicles directly into existing highway network without adaptation of the current infrastructure.

5.1.2.2 D3M with wide CAT lane

The three lanes of the Base Case are retained but are re-configured so that the dedicated CAT lane is wider than the 3.65m standard in 0.5m increments. The wider CAT lane is to enable uniform wheel wander to spread wheel loads over a wider area. Substandard lanes are provided for manual trucks and for passenger cars/vans, respectively. The conversion cost incurred relate to relocating road markings and road studs.

The widened CAT lane is expected to reduce rate of pavement deterioration for the dedicated lane. However, the narrower manual lanes would result in increased travel time cost.

5.1.2.3 D4M with narrow lanes

To determine if the accurate lateral tracking (zero wander) of CATs can be exploited to provide overall benefits, a narrow CAT lane 2.85m wide is provided within the existing paved area. Substandard lane width for manual trucks is also provided, alongside two substandard lanes cars and vans. This produced a substandard four-lane (D4M) section.

Conversion cost will involve removing and re-installing road marking and road studs on the carriageway to the new cross-section.

The below-standard CAT lane width is expected to worsen the pavement deterioration rate due to channelisation. However, the gain of an additional lane for manual vehicles should improve traffic flow and reduce vehicle operation cost.

5.2 Impact of CAVs on capital expenditure for highway schemes

5.2.1 Developing a conversion pricing method for CAV-enabled roads

Calculating the conversion costs involved determining the initial capital investment required to construct the engineering alternatives. This meant applying industry practices and historic pricing data from the construction industry. Total costs for each cross-section alternative was taken to include: (i) Conversion (construction) costs, made up of base cost of works, optimism bias and risks; (ii) Costs for preparing and administering the contract;

and (iii) Land costs (Infrastructure and Projects Authority, 2021). Highways England's library of works items was then analysed to determine whether - and how - the individual work items will be impacted when the existing Base Case Cross-section is remodelled to produce the cross-section alternatives (Department for Transport).

Table 5-1 contains the details and analysis results. The Series numbers and Works Items Descriptions follow those used by Highways England. The 'In Scope' column indicates whether the particular work item requires including within this research, and the final column provides justification for the inclusion or otherwise of that specific work item. Each work item was categorised as one of the following:

- Impacted by the introduction of CATs and so included in the base cost analysis,
- Impacted by the introduction of CATs but excluded due to research scope,
- Not expected to be impacted by the introduction of CATs.

In can be seen from the table that the below civil engineering works cost items will be impacted:

- Preliminaries
- Site Clearance
- Traffic signs and road markings

This approach ensured all possible costs were captured, hence reducing or eliminating the risk of inaccurate results due to accidental omissions.

Table 5-1 Scoping cost works items

SERIES	WORKS ITEM DESCRIPTION	IN SCOPE?	REASON
100	**Preliminaries**	**Yes**	**Conversion duration differs by scenario, hence time-related will be affected**
200	**Site Clearance**	**Yes**	**Extent of lane widths reconfiguration affect project footprint, and thus, the area of site clearance**
300	Fencing	No	Changes limited to paved carriageway
400	Road Restraints Systems	No	CATs will impact safety, but out of scope. No nearside barrier in the Base Case, and the offside barrier is unaffected.
500	Drainage and Service Ducts	No	Changes limited to paved carriageway
600	Earthworks	No	Changes limited to paved carriageway
700, 800, 900, 1000	Pavements	No	Changes limited to paved carriageway
1100	Curbs, footways, and paved areas	No	Changes limited to paved carriageway
1200	**Traffic signs and road markings**	**Yes**	**Road markings are determined by the specific scenario**
1300	Road lighting columns and brackets, CCTV masts and cantilever masts	No	Likely to be impacted, but outside research as relates to technology. Research focus is civil engineering infrastructure
1400	Electrical work for road lighting and traffic signs	Yes	See 1300 above
1500	Motorway communications	Yes	Diversion required for widening options
1600	Piling and embedded retaining walls	No	CATs have different loadings, but structures outside the scope
1700	Structural concrete	No	CATs have different loadings, but structures outside the scope
1800	Steelwork for structures	No	CATs have different loadings, but structures outside the scope
1900	Protection of steelwork against corrosion	No	CATs have different loadings, but structures outside the scope
2000	Waterproofing for structures	No	CATs have different loadings, but structures outside the scope
2100	Bridge bearings	No	CATs have different loadings, but structures outside the scope
2300	Bridge expansion joints and sealing gaps	No	CATs have different loadings, but structures outside the scope
2400	Brickwork, blockwork and stonework	No	CATs have different loadings, but structures outside the scope
2500	Special structures	No	CATs have different loadings, but structures outside the scope
2600	Miscellaneous	No	Mainly non-structural concrete. Minimal, but complex costs
2700	Accommodation Works, Statutory Undertakers, Provisional Sums	No	Changes limited to paved carriageway
3000	Landscape and Ecology	No	Changes limited to paved carriageway
5000	Maintenance Painting of Steelwork	No	Mainly determined by environmental factors

Once the affected items were identified, their quantities were calculated using the First Principles (or Bottom-Up) approach (Infrastructure and Projects Authority, 2021). This method allowed individual items to be quantified, and minor differences detected, thus enabling the comparison of different cross-section alternatives at a granular level. Measurements were taken in accordance with Method of Measurement for Highway Works (MMHW) (Money and Hodgson, 1992). Individual item costs were then obtained by applying published unit prices (AECOM, 2021).

5.2.2 Conversion works costs

The standard items and their unit rates for the relevant elements that from part of the conversion works, are shown below in Table 5-2.

Table 5-2 Standard items and costs, modified from industry sources (AECOM, 2018)

ITEM	UNIT	RATE (£ PER UNIT)
200 SITE CLEARANCE		
200.1 Site Clearance		
General site clearance (live dual carriageway)	m^2	0.66
200.2 Take Up or Take Down and Set Aside for Reuse or Remove To Store or Tip Off Site		
Removal of existing reflectorised thermoplastic road markings (200mm wide)	m	3.13
Road stud	nr	5.14
1200 TRAFFIC SIGNS AND ROAD MARKINGS		
Road Markings		
Thermoplastic screed or spray; Continuous line in reflectorized white; 200mm wide	m	1.85
Reflecting Road Studs		
Rectangular one way or bi-directional reflecting road stud with red or green or white catseye reflectors	nr	18.62

The cost of the works items was then calculated from:

$$W = \sum R_i Q_i \qquad \text{Equation 5-1}$$

Where;

W = work cost, in £

R_i = unit rate for item i, in £/unit quantity

Q_i = quantity for item i (in unit of measure).

Conversion (construction) cost is incurred before project opening as one-off

5.2.3 Cost of Preliminaries

Data produced by the National Audit Office, which analysed completed road projects, was used to calculate cost of Preliminaries. Cost values for 'Preliminaries' were determined by using typical cost distributions from completed road projects (Department for Transport, 2007).

All the design alternatives maintained the existing footprint of the road, with no widening; hence the land-take and statutory undertakers options would not incur any cost. Their percentages were, therefore, redistributed between the works cost and Preliminaries. The Table 5-3 below shows the results of the re-distribution analysis caried out for this study.

Table 5-3 Percentage breakdown of cost elements

Cost Element	Typical Construction cost breakdown (%)	Re-distributed breakdown for study (%)
Works costs	54	63
Preliminaries - Preparatory work	23	27
Preliminaries - Design & supervision	9	10
Land-take and compensation	7	0
Statutory undertakers	7	0
Total	100	100

For the purpose of selecting an Optimism Bias rate, the research is deemed as commensurate with feasibility design stage (Marsh, 2018), due to the level of uncertainty associated with road designs for autonomous vehicles. Therefore, a 44% uplift was applied (Mott MacDonald, 2002).

5.2.4 Results of conversion costings for modified highways

This sub-section focuses on the results of the initial conversion cost of different CAT lane options. The results are shown in Figure 5-5.

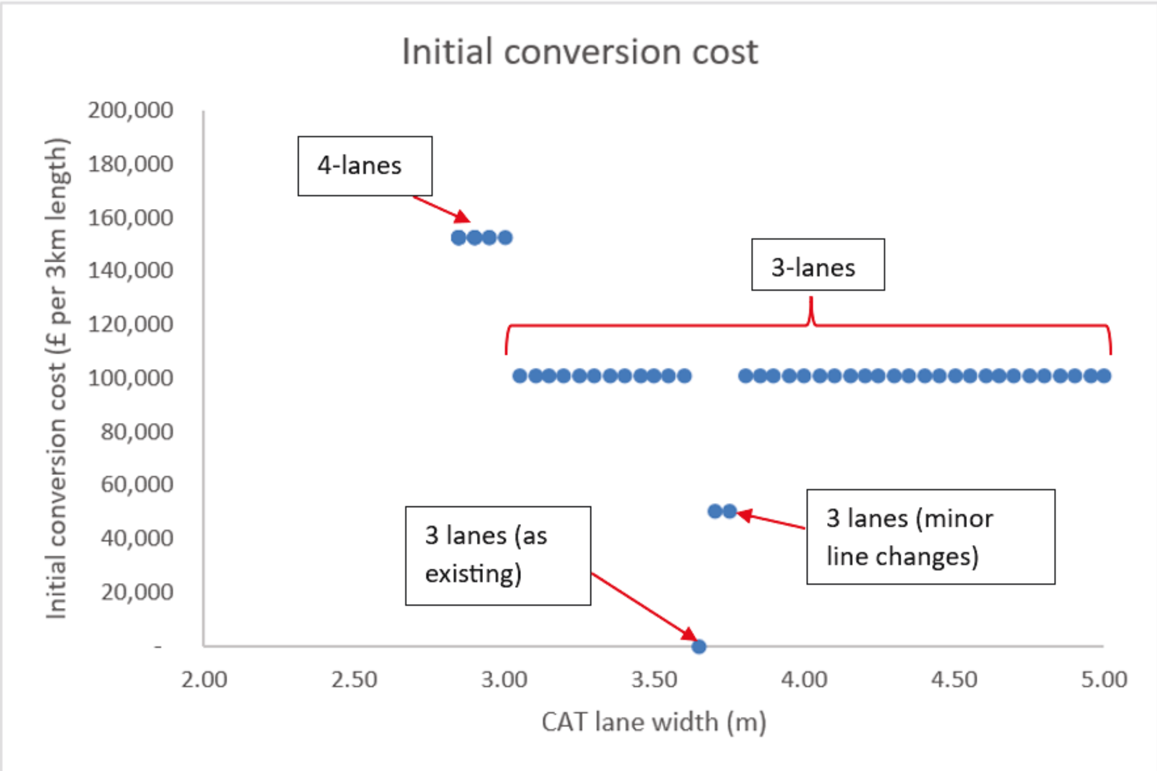

Figure 5-5 Initial cost of converting cross-sections

The graph represents discrete values of costs as the conversion costs are dependent on the number of traffic lane lines being removed and replaced to form the new cross-section. Therefore, the profile shows horizontal sections when the number of lane lines affected are the same, even if lane widths differ. Also, certain sections of the graph present sharp vertical trajectories for a 0.5m change in CAT lane width, such as from 3.60m to 3.65m CAT lane width. This is because of a change in the number of lane lines affected. The standard 3.65m CAT lane retains the existing lane, and incurs no cost.

Narrow CAT Lane options produced the highest cost of £152,000/3km length – because with this option, the carriageway configuration involves more work to create three lanes for MVs. This cost is the same for creating all CAT lanes between 2.85m and 3.05m, as the same number of lane marking changes are required. Hence the graph is horizontal for this range of CAT lane width.

For CAT lane width of 3.05 to3.65m, and 3.8 to 5m, the incurred conversion cost is about £100,000/3km length. This is because they all require moderate realignment of road markings. The three lanes of the original cross-section are maintained for these options, but with minor lane lines shifted. A standard CAT lane incurs no conversion cost (£0 per 3km section) as the existing carriageway remains unchanged cross-sectionally for introducing CAT.

Slightly above-standard CAT lanes of 3.70-3.75m incur conversion costs of about £50,000 per 3km length, only a third of the narrow CAT lane conversion cost, because the modifications are minor, with only a slight realignment of one of the existing lane road markings.

5.3 Quantifying vehicle operation and maintenance costs

The fourth and final stage involved operational costs, consisting of the following cost elements:

- Highway asset maintenance cost, especially pavement rehabilitation
- Travel time costs, which relate to the value of time of motorists
- Safety costs, and
- Fuel consumption

These operational costs are functions of traffic volumes, composition, and behaviour, as well as lane widths. Determining the total maintenance costs involved complex analysis.

MPRs values from 10% to 90%, with 10% increments were used to capture the very low to very high range of market penetrations. In addition to these core MPRs, 5% and 95% were then also analysed to capture low and high extremes MPRs as well. In all, 11 MPR values were included in the analysis.

5.3.1 Pavement failure analysis for shared CAT/MT carriageways

5.3.1.1 Approach framework and justification

Pavement deterioration rates were determined using the TxME mechanical-empirical software describe in Section 4.1.2.1 above. Although its mechanical models (multilayer elastic system, fracture mechanics, and material visco-elasticity) are like other pavement software analysis programmes (such as MEPDG and AASHTOWare Pavement ME Design), TxME empirical models employ relationships that link stresses/strains to rutting and cracking performance. These performance criteria were observed from field data at the National Center for Asphalt Technology (NCAT) test track, Federal Highway Administration (FHWA) Accelerated Loading Facility (ALF), and several other test sections in the state of Texas (Hu et al., 2013). TxME's validation/calibration against a broad range of field data increases the robustness of results.

Another reason for using TxME is that it provides an efficient and flexible interface for modifying and observing impacts of CAT and MT lane widths changes.

Also, normal and uniform wheel wander distribution modes can be analysed. Moreover, TxME enables a wide range of traffic loads to be assessed, which was useful for this study in providing good statistical performance of the generated results.

5.3.1.2 Traffic assessment

Annual average daily traffic (AADT) for 2019 was used as the base year, as it is the most recent, pre-COVID19 pandemic year (Department for Transport, 2020b). The results are therefore more likely to represent normal traffic trends post-pandemic when forecasting future years. The HGV proportion of the AADT was calculated as 11.6%, based on 2019 traffic flow volumes categorised by vehicle type (Department for Transport, 2021). For the purposes of the pavement analysis, the traffic volumes for buses and coaches were added to the HGV volumes as these impact pavement performance as well (Highways England, 2020b).Yearly future traffic volumes were then forecast to obtain data for the design period. Forecasting future traffic involved direct application of growth rates published by the UK government. However, because these published growth rates were in five-year intervals, linear interpolation was used to obtain growth rates for intermediate years (Department for Transport, 2018b).

Forecasting was based on a project opening year of 2025, as fully autonomous vehicles are predicted to be introduced by that time (KPMG International, 2019). A 20-year design period was chosen so that the analysis is consistent with UK's standard pavement design life assessment criterion for existing roads, as opposed to 40-year design life which would have been more appropriate were widening options included in the analysis. The results of the design traffic data analysis are shown in Table 5-4.

Table 5-4 Calculated design traffic for pavement analysis*

	Year	All Vehicles Growth rate (from 2019)	AADT	HGV %	HGV Growth rate (from 2019)	HGV Average Daily Flow (F)
	2019	-	**83,300**	11.6	-	9,663
	2020	**8.70**	90,547	10.8	**1.20**	9,779
	2021	9.88	91,530	10.7	1.30	9,788
	2022	11.06	92,513	10.6	1.40	9,798
	2023	12.24	93,496	10.5	1.50	9,808
	2024	13.42	94,479	10.4	1.60	9,817
	2025	**14.60**	95,462	10.3	**1.70**	9,827
	2026	15.72	96,395	10.2	1.94	9,850
	2027	16.84	97,328	10.1	2.18	9,873
	2028	17.96	98,261	10.1	2.42	9,897
	2029	19.08	99,194	10.0	2.66	9,920
	2030	**20.20**	100,127	9.9	**2.90**	9,943
	2031	21.52	101,226	9.9	3.42	9,993
	2032	22.84	102,326	9.8	3.94	10,044
	2033	24.16	103,425	9.8	4.46	10,094
	2034	25.48	104,525	9.7	4.98	10,144
	2035	**26.80**	105,624	9.7	**5.50**	10,194
	2036	27.92	106,557	9.6	6.06	10,248
	2037	29.04	107,490	9.6	6.62	10,302
	2038	30.16	108,423	9.6	7.18	10,357
	2039	31.28	109,356	9.5	7.74	10,411
	2040	**32.40**	110,289	9.5	**8.30**	10,465
	2041	33.34	111,072	10.0	8.84	10,517
	2042	34.28	111,855	10.6	9.38	10,569
	2043	35.22	112,683	11.3	9.92	10,621
	2044	36.16	113,421	12.0	10.46	10,674

*Bold text data are from secondary sources; Data in regular text style were calculated for this research

5.3.1.3 Wheel load analysis

The Total Equivalent Single Axle Loads (ESAL) over the design period was then derived from DMRB pavement design standard (Highways England 2020b), thus:

$$\text{ESAL} = 365 \cdot P \cdot D \cdot 10^{-6} \cdot \sum_{i=1}^{n} F_i$$

Equation 5-2

where:

P = HGV split in the direction of the carriageway. Assuming equal split between the two directions yields P = 50%

D = Average damage factor, calculated from vehicle class wear factors as 3.57, Figure 5-6.

F_i = Average daily HGV flow for the *i*th year of the project opening (Table 5-4 final column)

n = Design period in years, taken as 20, as previously explained

Hence, from the equation above, design traffic loading ESAL is 132msa (million standard axles).

Vehicle Category	Damage Factor
Buses and Coaches	3.9
2-axle rigid	0.6
3-axle rigid	3.4
4-axle rigid	4.6
3 and 4-axle articulated	2.5
5-axle articulated	4.4
6-axle articulated	5.6
Average Damage Factor	**3.57**

Figure 5-6 Damage factors (Used information under Open Government License v3.0)

The study then assumed that all CATs would use the dedicated lane, as autonomy should increase lane discipline. Trucks distributions in the manual lanes, however, was taken to follow lane utilization models used in current pavement designs, as presented in DMRB CD 224 Traffic Assessment, Table 2.21 (Highways England 2020b), thus:

$$ESAL_{MT} = (ESAL - ESAL_{CAT}) \times \{(89 - [(0.0014) \times (ESAL - ESAL_{CAT})]\} \quad \text{Equation 5-3}$$

where $ESAL_{MT}$ is the traffic loading for manual trucks in the heaviest loaded lane, ESAL is the total design traffic calculated above, and $ESAL_{CAT}$ is ESAL in CAT lane.

The ESALs for CATs and manual trucks for the different CAT penetration rates are shown in Table 5-5.

Table 5-5 MPRs, and CAT and MT lanes traffic loadings

CAVs Ratio (%)	CAT Lane (msa)	MT Lane (msa)
0	0	117.2
5	6.6	111.4
10	13.2	105.5
20	26.4	93.8
30	39.6	82.1
40	52.8	70.4
50	66	58.7
60	79.2	47.0
70	92.4	35.2
80	105.6	23.5
90	118.8	11.7
95	125.4	5.9
100	132	0.0

5.3.1.4 Design of test pavement structure and foundation

The analysis was performed using a 360mm three-layer dense-graded asphalt concrete pavement. This was designed to correspond to the 132msa total traffic loading calculated in Section 5.4.1.2 above. The design was done using the UK DMRB method (Highways England, 2020d). This is shown in Figure 5-7. The design curve for Foundation Class 2 was selected here, as this applies to most traffic situations, i.e., where the long-term surface modulus strength is ≥ 100MPa (Highways England, 2020c).

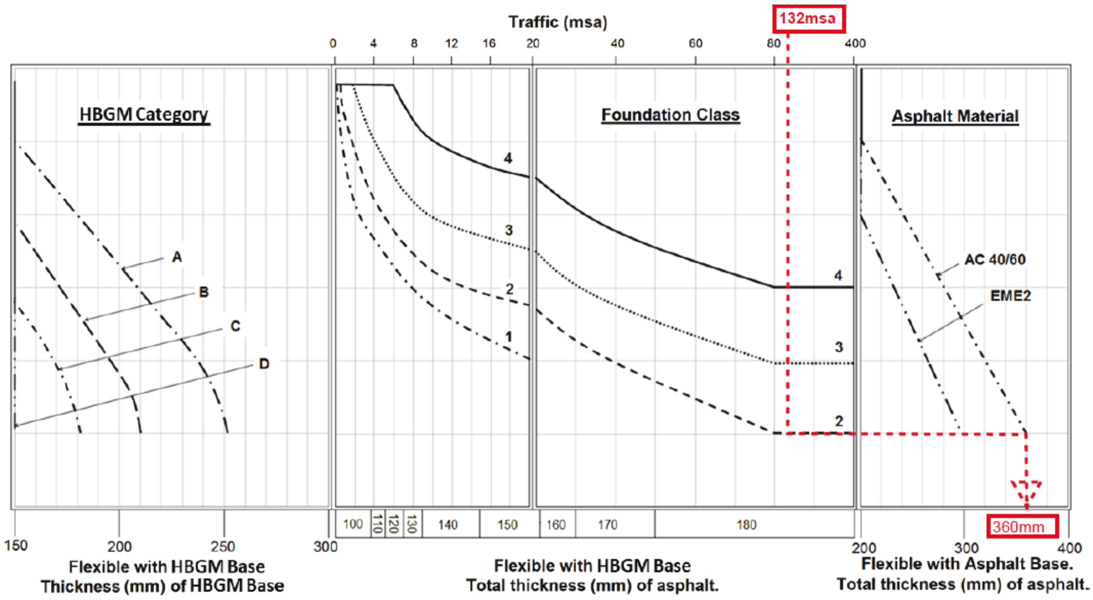

Figure 5-7 Design of test pavement structure. Interpreted from Highways England (2020d)

The foundation design for 100MPa modulus (14.5ksi) requires 200mm of granular sub-base (Highways England, 2020c). The design of this is shown in Figure 5-8.

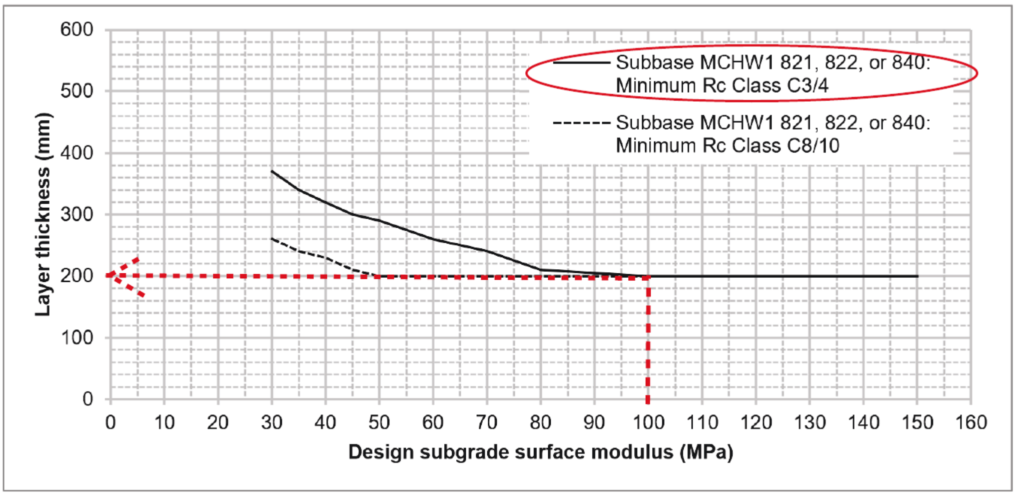

Figure 5-8 Test pavement foundation design. Interpreted from Highways England (2020c)

The test pavement structure as used in this research analysis – together with its foundation - is shown in Figure 5-9.

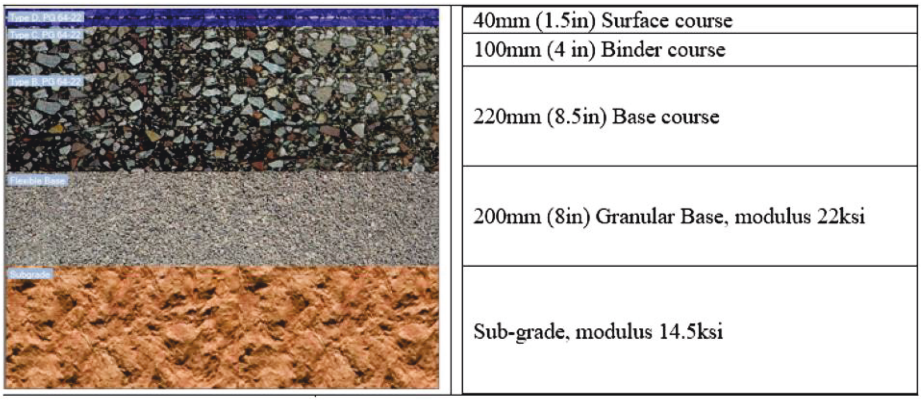

Figure 5-9 Pavement structure for analysis

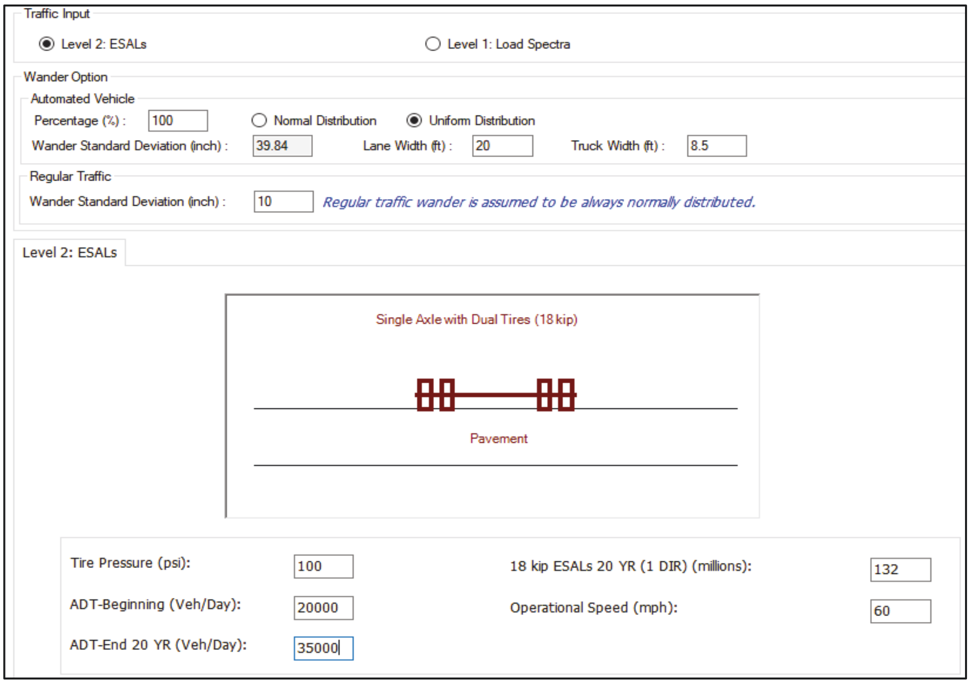

Figure 5-10 Traffic input data for TxME software

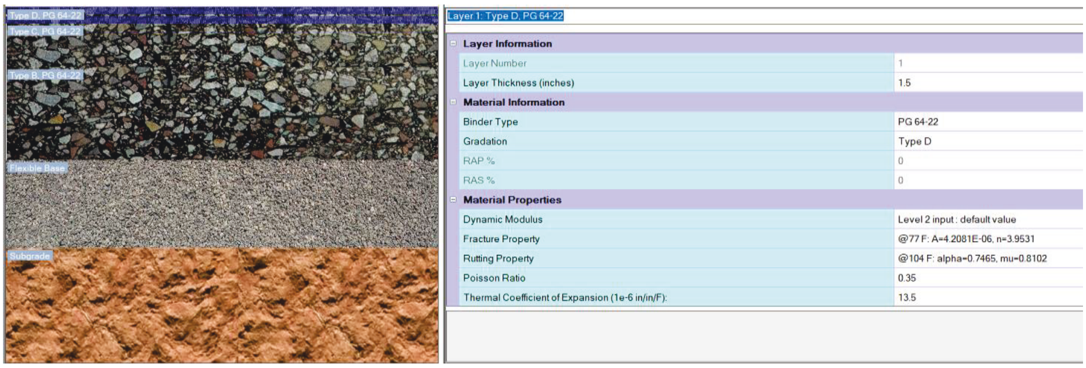

Figure 5-11 Pavement physical and material properties input for TxME analysis

5.3.1.5 CAT lane pavement failure

Pavement failure rates were measured for sub-standard lane widths (75mm lateral wheel wandering standard deviation from the mean, for 2.85m lane width), through to above-standard lane widths (1m deviation for 5m wide lane) (Zhou, Hu et al. 2019a, Zhou, Hu et al. 2019b).

Propagation of cracking damage and rut depth over time was then collated from the TxME results, from which maintenance frequency was calculated.

5.3.1.6 MT lane pavement failure

Manual trucks were also modelled in TxME using a normal wander distribution with a 250mm standard deviation for a standard 3.65m lane width. The results are plotted in Figure 5-12 below.

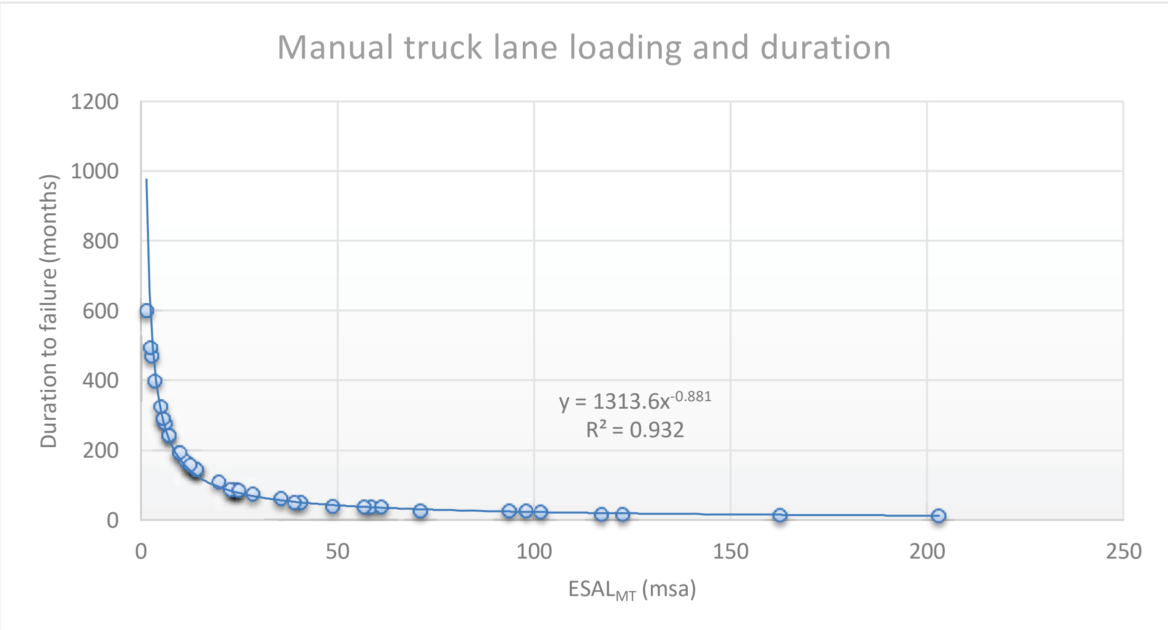

Figure 5-12 Manual truck lane loading and pavement duration

If D_M is the duration to failure for a standard width MT lane, then from the regression model of the above curve;

$D_M = 1313.6\ (ESAL_{MT})^{-0.881}$ ---------------- Equation 5-4

5.3.1.7 Accounting for the effect of manual truck lane width

The effect of lane width on pavement failure frequency was determined by developing a regression model, deduced by analysing traffic load distribution data (Pinard and Hongve, 2020). This is reproduced here in Table 5-6.

Table 5-6 Lane width adjustment factors for traffic loading (Pinard and Hongve, 2020)

Cross section	Paved width	Corrected design traffic loading (ESA)	Explanatory notes
Single carriageway.	< 3.5m.	Double the sum of ESAs in both directions.	The driving pattern on this cross-section is very channelized.
	Min. 3.5m but less than 4.5m.	The sum of ESAs in both directions.	Traffic in both directions uses the same lane, but not all in the same wheel tracks as for the narrower road.
	Min. 4.5m but less than 6m.	80% of the ESAs in both directions.	To allow for overlap in the centre section of the road.
	6 m or wider.	Total ESAs in the heaviest loaded direction.	Minimal traffic overlap in the centre section of the road.
More than one lane in each direction.		90% of the total ESAs in the studied direction.	The majority of vehicles use one lane in each direction.

The regression model developed is as shown in Figure 5-13. The data points for the lane widths use the mid-point of the range.

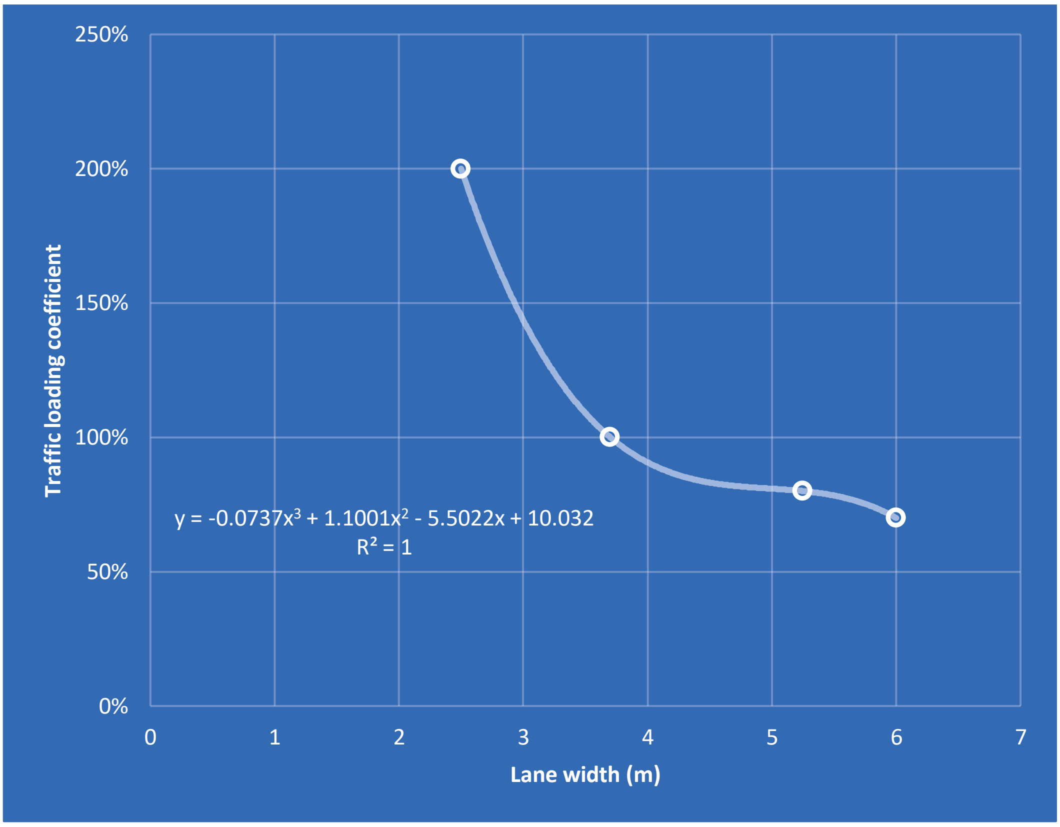

Figure 5-13 Traffic loading and lane widths

$F = -0.0737x^3 + 1.1001x^2 - 5.5022x + 10.032$ Equation 5-5

Where F is a unitless factor to correct the Equivalent Standard Axle for the lane width ‘x’, in m.

5.3.1.8 Pavement rehabilitation costs

Failure frequencies were then found, and cost estimation methods similar to those described above in Section 5.3 for initial capital investment budgets were then used to calculate costs for removing and replacing the layers of damaged pavement.

5.3.1.9 Pavement deterioration and maintenance thresholds

The TxME software analysis results for rutting and fatigue cracking failure are plotted in Figure 5-14 and Figure 5-15, respectively. The profiles of the graphs are presented as steps rather than smooth curves because the output from TxME are reported as discrete figures. For instance, for standard deviation SD = 76mm (3inch), 20%MPR, the rut depth is the same from Month 5 to Month 11, this will show as a horizontal line on the curve, before going vertical but slightly slanted at Month 12.

Rut depth failure threshold was taken at 10mm (0.4in). The fatigue cracking failure threshold was taken at 1% of a standard wheel track width of 0.9m (Zhou et al., 2019a, Highways England, 2022). These threshold points were chosen as pavement rehabilitation can be undertaken to restore serviceability, and before whole-sale repairs become necessary (Powell et al., 1984). It was observed that in all cases, the pavement reached rutting failure before the cracking threshold was reached. This was likely due to the thickness of the structural pavement layers, which improved resistance to reflective cracking.

During normal operations for CAT lanes, the wider lanes deteriorate slower, as the wheel loads spread over a wider area due to increased lateral deviation of wheel load which is spread uniformly; narrow lanes led to concentrated wheel loads. Scenarios with higher CAT proportions caused the CAT lane to deteriorate quicker due to the higher number of imposed wheel loads. This shows that, although the uniform wandering model of CATs increases pavement longevity, the high compliance of CATs in terms of using the dedicated lane increases pavement failure rate.

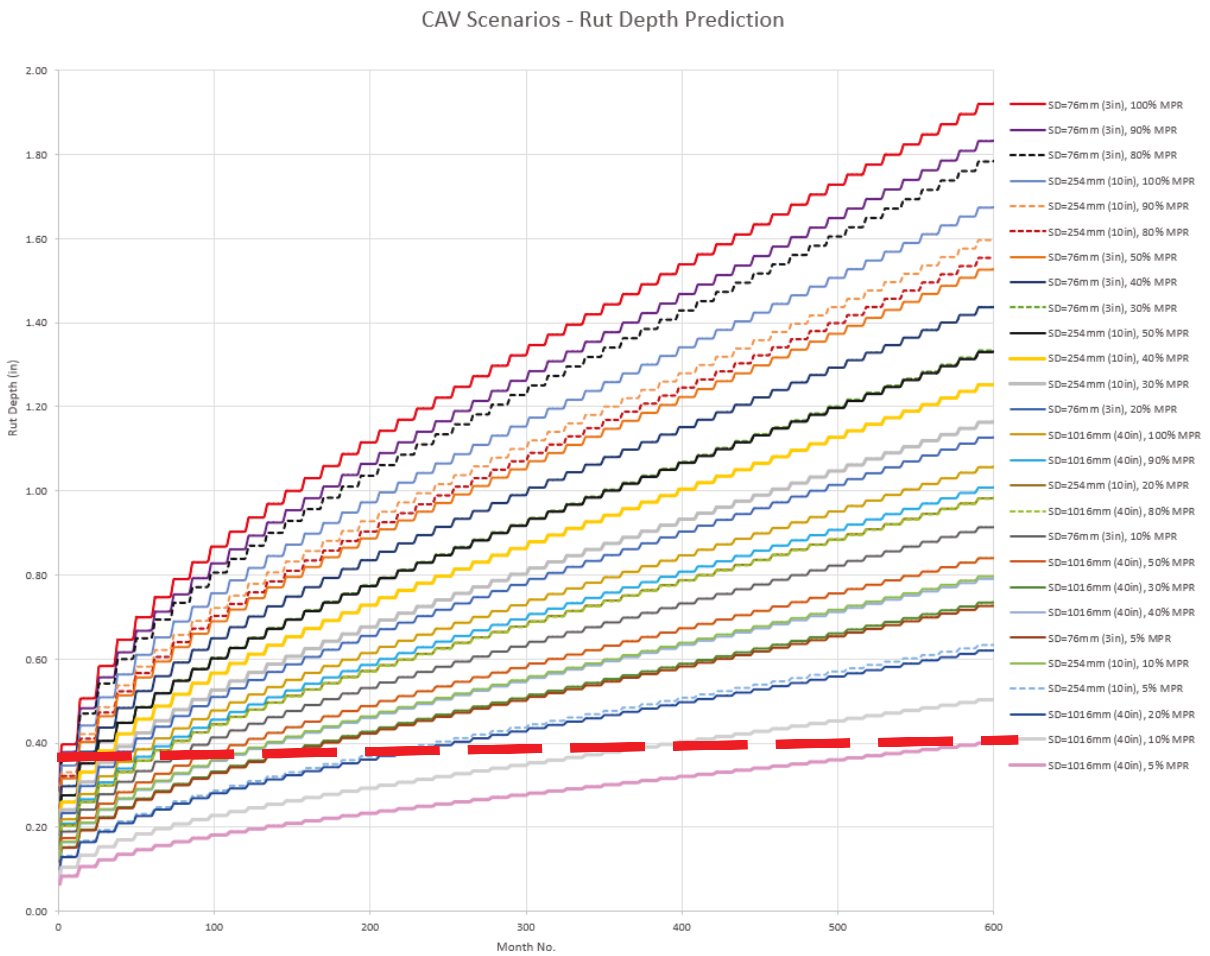

Figure 5-14 Rut depth propagation, highlighting 0.4 in failure line

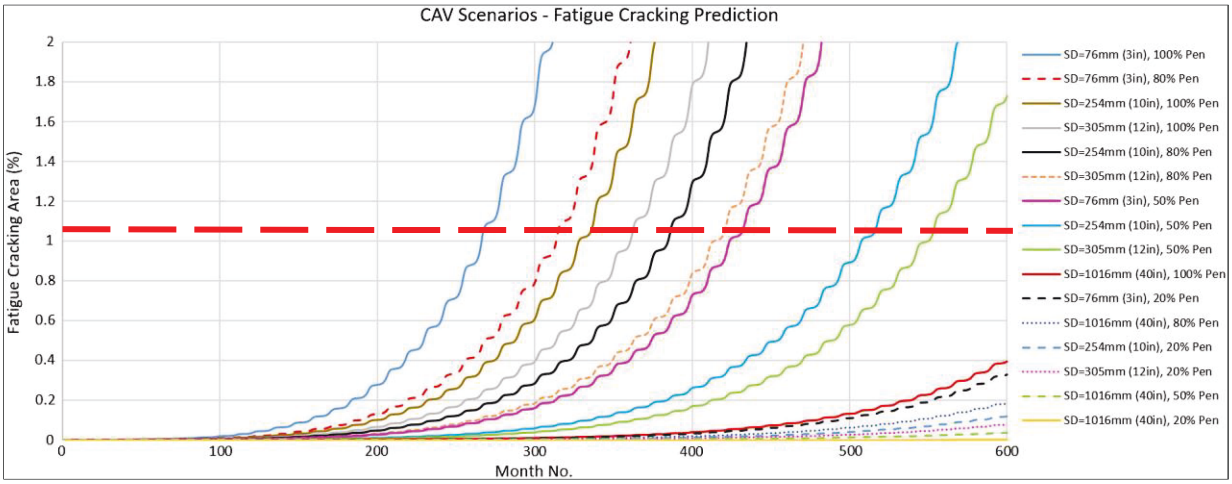

Figure 5-15 Cracking failure analysis with 1% failure threshold shown

5.3.2 Results and interpretations of pavement failure frequency/maintenance costs:

The changes of the maintenance costs with respect to cross-section alternatives for each of the investigated MPR levels are shown in Figure 5-16.

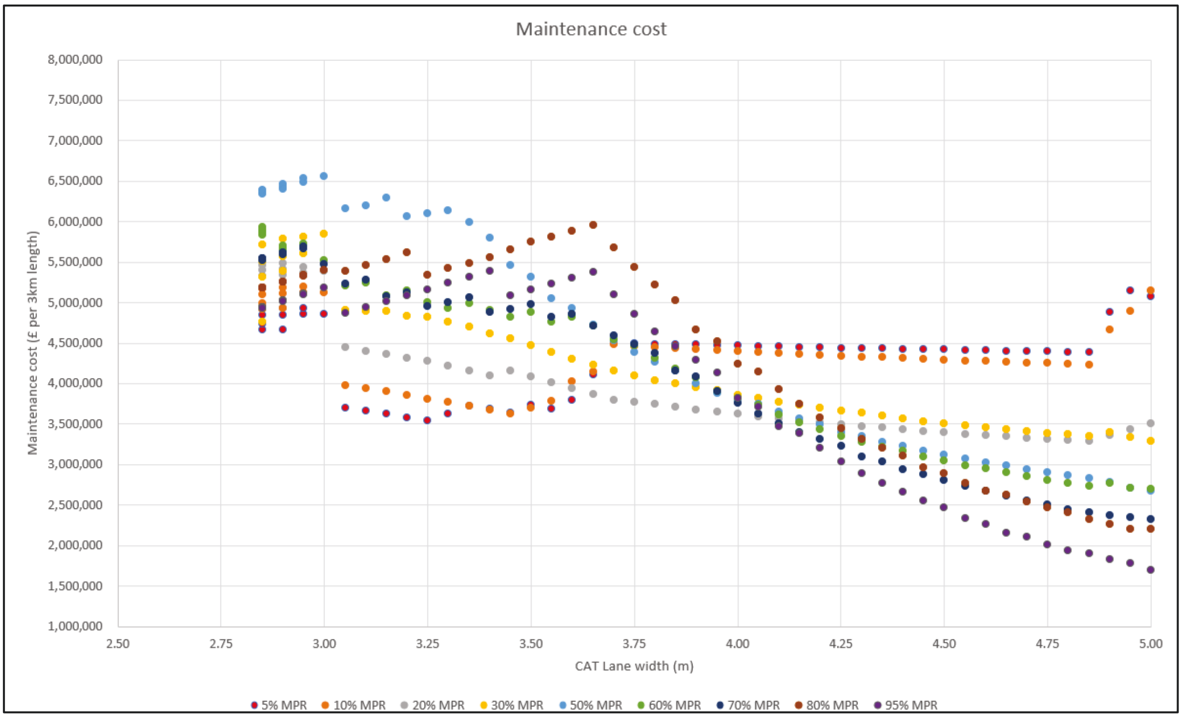

Figure 5-16 Maintenance costs

It can be observed from the plots that at the low MPRs of 5, 10 and 20%, the maintenance costs increases as the CAT lane width approaches 5m. This is because, at these low penetration rates, there is a high number of manual trucks, and these are squeezed into a relatively narrower lane due to CAT lane being wide. This cause the manual truck lane to fail more rapidly, leading to the cost increases for this higher CAT lane widths for the low MPRs.

The scenario that produces the lowest maintenance cost (£1.7m per 3km length) occurs at very high penetration rate of 95% when a very wide CAT lane of 5m is implemented. The highest maintenance cost (£6.6m per 3km length) occurs for mid-range MPR of 50%, when both CAT and MT lanes have sub-standard 3m wide lanes.

The minimum cost at very low penetration rates (5-10%) is £3.6m per 3km length, and this corresponds to a slightly sub-standard CAT lane width of approximately 3.30m. The highest maintenance cost occurs for the extremely wide CAT lane of 5m, where maintenance cost rises to just over £5m per 3km length. This is because, the low CAT traffic implies high MT traffic, and a reduced CAT lane means a wider MT lane, which then reduces the pavement failure rate of the MT lane, the converse is also true; with wider CAT lane, all the high-volume MT vehicles have to squeeze within a narrower MT lane, causing quicker failure, and hence, increased maintenance cost. The exception is for the very narrow CAT lane options of under 3m. In these scenarios, the CAT lane failure frequency increases exponentially, and negates the reduced failure benefits from the wider MT lane.

As penetration rates increase (≥20%), the minimum maintenance cost occurs for scenarios with much wider, above-standard, CAT lane widths. This cost ranges from £1.7m per 3km length for 95% MPR, 5m CAT lane, to £3.3m per 3km length for 20% MPR, 4.85m wide CAT lane. For low to high MPRs, (20% to 70%) the maximum costs occur when sub-standard CAT lane width (less than 3m wide) is used. And from high to very high MPRs, the highest cost occurs at standard CAT lane width of 3.65m.

5.4 Assessing safety implications of dedicated connected autonomous truck lanes

Data collected under varying conditions has shown that accidents that can be attributed to human error is consistently around - or higher than - 90% (Society of Motor Manufacturers and Traders, 2017). Accident statistics are expected to improve with the penetration of CAVs, because fundamental to driverless vehicle systems is the reduced or excluded human control.

It has been estimated that over 80% of all road accidents can be avoided or significantly mitigated based on CV techniques (Zhang et al., 2018).

Under this research study, safety analysis and prediction models were used to determine the number of accidents that would occur for the various scenarios. Accident monetary values were then derived from DfTs WebTAG data, presented within the COBALT data sheets (Department for Transport, 2018c).

The accident number calculations ae outlined below.

5.4.1 Establishing base safety

For this study, historic accident data was obtained from the Department for Transport's database RAS20001 (Department for Transport, 2018a).

The most recent data at the time of the study that contained comprehensive accident information was for the year 2017. This is reproduced in Table 5-7 below.

Table 5-7 2017 Accidents: vehicle type and severity (Department for Transport, 2018a)

	Number of vehicles/rate per billion vehicle kilometres				
	2013	**2014**	**2015**	**2016**	**2017**
Pedal cycles					
Fatal	121	122	113	110	117
Rate	24	22	22	20	22
Fatal or serious	3,471	3,775	3,565	3,737	4,071
Rate	689	678	682	673	774
All severities	20,049	21,979	19,440	19,047	18,954
Rate	3,981	3,950	3,719	3,429	3,603
Motorcycle riders					
Fatal	356	375	398	365	379
Rate	82	84	89	80	85
Fatal or serious	5,485	5,933	5,709	6,178	6,337
Rate	1,267	1,329	1,279	1,358	1,424
All severities	19,538	21,378	20,996	20,423	19,204
Rate	4,514	4,789	4,704	4,489	4,316
Cars					
Fatal	1,810	1,831	1,781	1,943	1,897
Rate	4.7	4.6	4.5	4.8	4.6
Fatal or serious	22,802	23,896	23,372	25,759	26,398
Rate	59	61	59	63	64
All severities	185,769	195,576	188,872	185,307	174,143
Rate	481	496	474	456	425
Buses or coaches					
Fatal	69	61	64	57	55
Rate	15	14	15	14	14
Fatal or serious	767	777	702	674	776
Rate	170	172	163	170	200
All severities	5,896	6,103	5,381	4,998	4,998
Rate	1,308	1,353	1,250	1,258	1,288
Vans / Light goods vehicles					
Fatal	153	169	167	186	189
Rate	2.2	2.3	2.2	2.4	2.3
Fatal or serious	1,704	1,910	1,903	2,041	2,132
Rate	25	26	25	26	26
All severities	12,686	14,043	13,876	13,125	12,479
Rate	185	194	184	166	154
Heavy goods vehicles					
Fatal	270	265	298	273	259
Rate	11	10	11	10	9
Fatal or serious	1,277	1,247	1,291	1,230	1,209
Rate	51	48	48	46	44
All severities	6,524	6,873	6,470	5,819	5,136
Rate	259	266	241	217	187
All vehicles[2]					
Fatal	2,846	2,902	2,899	3,022	2,963
Rate	5.8	5.7	5.6	5.7	5.6
Fatal or serious	36,020	38,070	37,104	40,391	41,768
Rate	73	75	72	77	79
All severities	252,913	268,527	257,845	252,500	238,926
Rate	512	530	501	480	449

The data was then analysed, providing the base-case accident rates for typical motorways, categorised by levels of severity. Total billion vehicle kilometres for HGV in 2017 = 259 / 9 = 27.4.

Hence, HGV fatality rate = 259 / 27.4 = 9.45. Serious injury = (1,209 – 259) / 27.4 = 34.67, and injury only = (5,136 – 1,209) / 27.4 = 143.33. Table 5-8 below summarises the accident rates.

Table 5-8 Accident rates by severity

ACCIDENT SEVERITY	RATE (PER BILLION VEH-KM)
Fatal	9.45
Serious	34.67
Slight	143.33

The monetary value of each accident type was also taken from DfTs WebTAG data, presented within the COBALT sheets (Department for Transport, 2018c).

Table 5-9 Breakdown and total accident costs (Department for Transport, 2018c)

Casualty type	Net output	Willingness to pay	Medical & ambulance	Total
Fatal	107,798	1,544,006	925	1,652,729
Serious	20,765	151,148	12,579	184,492
Slight	2,195	11,064	931	14,191
Average, all casualties	6,551	52,349	2,905	61,804

5.4.2 CAVs safety profile

The accident rates for the scenarios were then calculated using the exponential model developed by a collaboration of US and China universities (Xiao et al., 2021).

$$SIR = 0.0393e^{(2.7789 \times MPR)} \qquad \text{Equation 5-6}$$

Where SIR is Safety Improvement Rate, and MPR is the market penetration rate.

This model is selected for this research because, in the view of the authors, it is the most robust available model for estimating accidents relating to CAVs; the study used a meta-analysis approach to produce the model, which led to a new assessment indicator, the Safety Improvement Rate (SIR), enabling accident analysis for CAVs to be normalised and universalised. In addition, the study covered a wide range and variety of MPRs (from 10%

to 90%, and at 10% intervals), making it more encompassing than other CAV accident rate estimation models (Adomah, 2020, Sander and Lubbe, 2018, Li et al., 2017b).

However, it must still be noted that this model is based on highway operational regime with mixed CAVs and MVs. Accident patterns for such driving regimes are expected to be different from dedicated CAT lane conditions, so for this study, accidents within the dedicated CAT lane were based on 100% MPR. This could be an over-estimation of the number of accidents, because the CAV/MT interactions in non-dedicated lane scenarios are likely to be more complicated, and hence more accident prone, compared to dedicated lane arrangements.

5.4.3 MVs accident rates

For manual vehicles, the highways' cross-sectional configuration and lane widths impact the rate of accidents. Data presented by consultants at Goodell-Grivas was analysed to quantify this relationship (Zegeer et al., 1980). The outcome of the data analysis is present in Table 5-10. Then, in Figure 5-17, the model obtained from this analysis and used to calculated accident rates is shown.

Table 5-10 Lane widths and accident rates

LANE WIDTH (m)	ACCIDENT RATE (PER MILLION VEH-KM)	NORMALISED ACCIDENT RATE (PER MILLION VEH-KM)
2.1	2.58	2.10
2.4	2.28	1.85
2.7	1.88	1.53
3.0	1.78	1.45
3.4	1.28	1.04
3.7	1.23	1.00
4.0	1.35	1.10

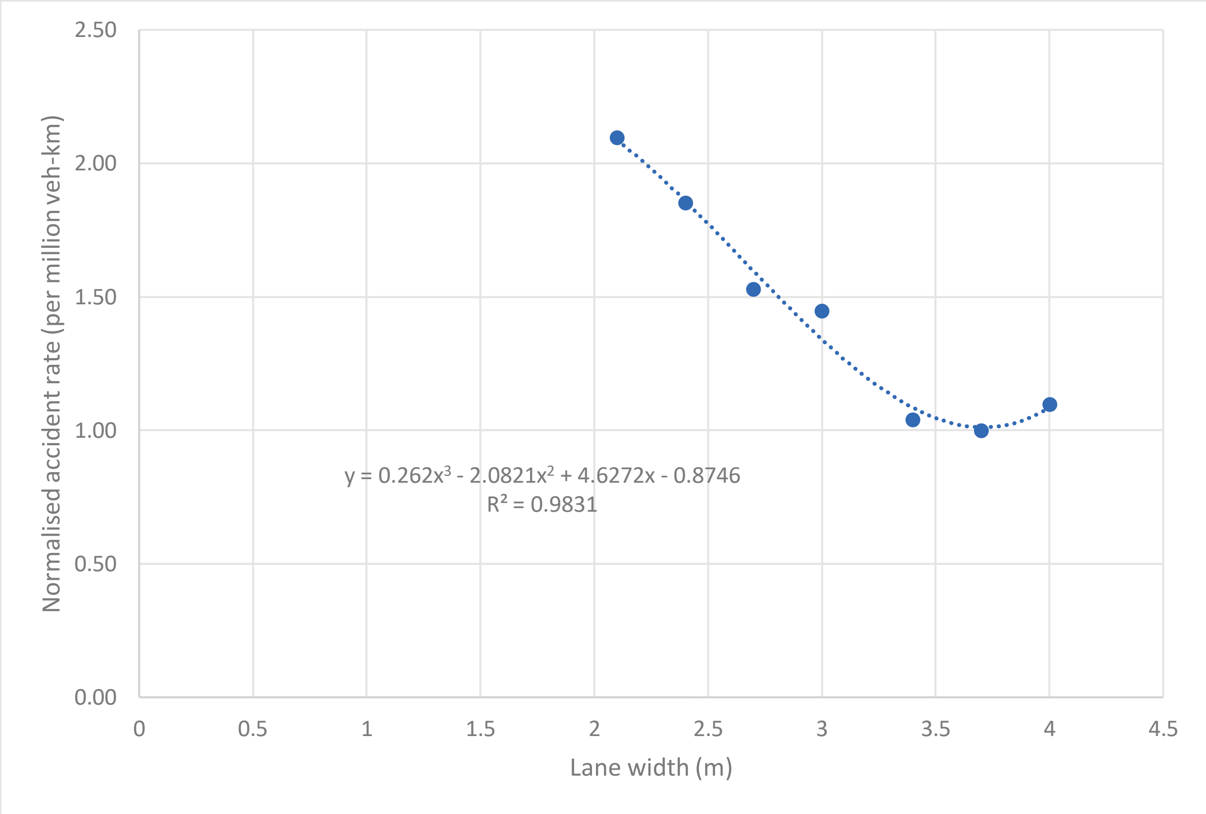

Figure 5-17 Model derivation for lane widths and accidents

It can be observed from the data recorded by Goodell-Grivas that accident rates reduce with increasing lane widths. This is because, when lanes are narrow, there is an increased chance of vehicles in one lane grazing other vehicles in adjacent lanes, leading to side-swipe type collisions. The exception is that, beyond the standard 3.65m, increasing the lane width results in higher accident rates. This is likely because, at wider lane widths, there may be confusion caused to drivers that more than one vehicle stream could occupy the same lane, leading to collisions.

5.4.4 Accidents rates and safety profile from introducing CAT lanes

A representative sample (very low, medium and very high) of the analysed accident cost information is depicted below in Figure 5-18.

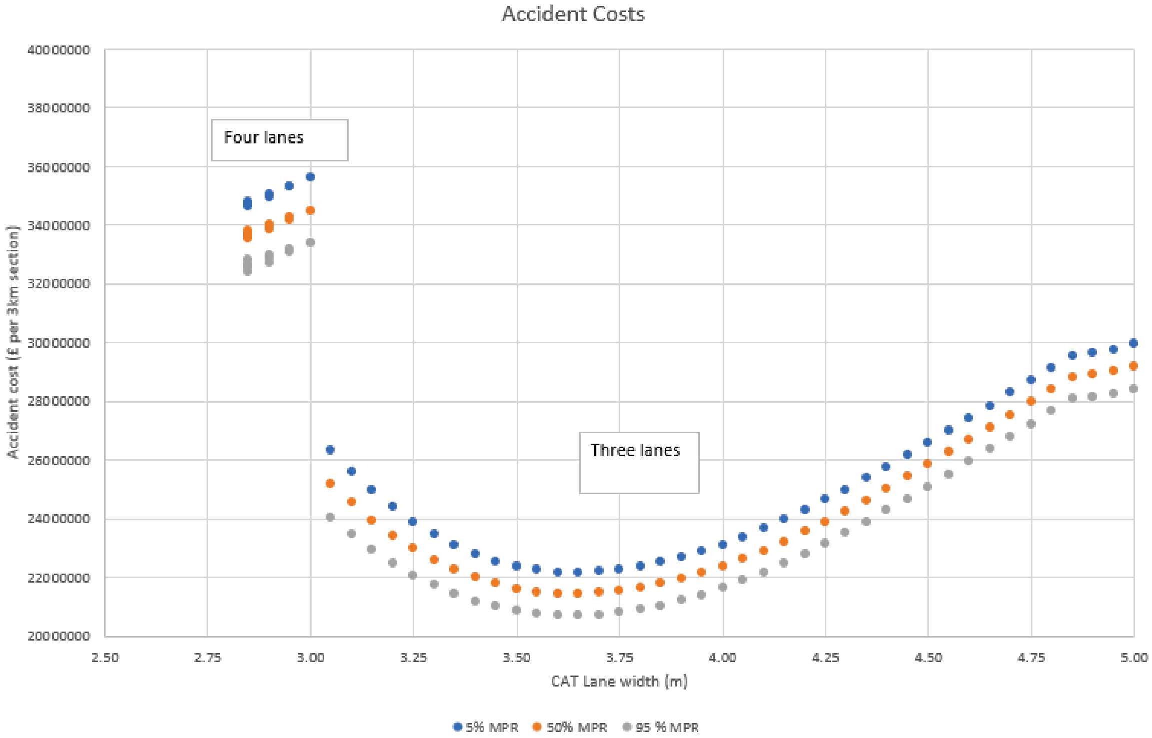

Figure 5-18 Accident costs for selected MPRs

The graph is in two parts: upper part representing higher accident cost, and the lower potion representing lower accident cost.

The upper graph corresponds to four lane scenarios. With these alternatives, the CAT lane is very narrow (between 2.85m and 3m), allowing two very narrow PC lanes to be fashioned out of the remaining carriageway width. The accident costs here are much higher here because the two PC lanes, which facilitate better traffic flow, are so narrow that side-swipe accidents are more frequent. Within this part of the graph, accident costs also increase with increasing CAT lane width, because wider CAT lane implies the MV and PC lanes are narrower, increasing accident frequency in these lanes.

The lower curve is the accident cost profile for the three lane options. With wider CAT lane width of 3.05m to 5m, there is not sufficient space to install a fourth lane. Due to the lane redistribution constraints, a standard CAT lane implies standard manual vehicle lanes (effectively keeping the standard DMRB cross-sections as is). And for manual vehicles (both PCs and MTs), the best safety performance occurs at the standard lane widths: very narrow lanes reduce lateral clearance between lanes, increasing accident risks, and above standard lane widths presents the illusion that two cars may fit side-by-side into one wide lane, resulting in increased merge-type accidents.

As a result, the lowest accident cost occurs for standard CAT lane width for all MPRs. The highest accident cost occurs for 3m lane width.

Accident costs decrease with increasing MPR, due to the increased safety of CATs over manual vehicles. Overall, the lowest accident cost is £20.7m per section (3km length) for 95% MPR. The highest accident cost is £35.6m per 3km length, for 3m wide CAT lane for 5% MPR.

5.5 Fuel and energy consumption variability

5.5.1 Overview of methods

Another component of the whole life costing is comparing fuel consumption characteristics of different scenarios. This has repercussions for both greenhouse gas emissions and vehicle maintenance costs.

DfT's WebTAG Databook was reviewed to obtain consumption and carbon dioxide emission rates, and to forecast the choice of fuel type based on vehicle categories, over the design period of 2025 to 2044. The Consumption rates were calculated from mathematical model:

$$L = (a/v + b + c.v + d.v^2)\ k \qquad \text{Equation 5-7}$$

Where: L is the consumption, l/km

v is average speed, km/hr,

a, b, c, d are parameters based on vehicle type (see Table 5-11 below).

k is a factor introduced specifically for this study, to account for the fuel consumption reduction anticipated for CAT in platoon conditions.

For regular vehicles, k = 1, and for CAT, k = 0.87, as CAT platooning is estimated to produce 13% reduction on fuel consumption (hence reduction in emissions), compared to manual trucks (McAuliffe et al., 2018).

The speeds (v) were based on the actual speeds calculated above in Section 5.8.1, where attainable speeds were shown to be influenced by posted speed limit, cross-section configuration, lane widths, traffic demand volumes and frequency of maintenance works.

Table 5-11 Fuel consumption parameters (Department for Transport, 2018c)

Fuel consumption parameter values litres per km						
	Parameters				Min speed	Max speed
Vehicle Category	a	b	c	d	kph	
Petrol Car	0.45195	0.09605	-0.00109	0.000007	10	130
Diesel Car	0.48191	0.06909	-0.00066	0.000005	10	130
Petrol LGV	0.34435	0.19309	-0.00303	0.000020	10	120
Diesel LGV	0.46348	0.11328	-0.00163	0.000014	10	110
OGV1	2.69628	0.14306	-0.00103	0.000011	12	85
OGV2	5.66560	0.29422	-0.00195	0.000012	12	85
PSV	3.36019	0.29525	-0.00321	0.000024	12	85
Energy consumption parameter values (kWh per km, 2015)						
Electric Car		0.219				120
Electric LGV		0.233				120
Electric OGV1						
Electric OGV2						
Electric PSV						

The fuel that various vehicle categories would use during the design life of the highway design scheme derived by reviewing information within DfT's WebTAG. The predicted fuel type by vehicle category is reproduced below in Table 5-12.

Table 5-12 Predicted fuel type use by vehicle (Department for Transport, 2018c)

	Proportion of cars, LGV & other vehicle kilometres using petrol, diesel or electricity											
	Cars			LGV			OGV1		OGV2		PSV	
Year	Petrol	Diesel	Electric	Petrol	Diesel	Electric	Diesel	Electric	Diesel	Electric	Diesel	Electric
2004	**73%**	**27%**	**0%**	**8%**	**92%**	**0%**	**100%**	**0%**	**100%**	**0%**	**100%**	**0%**
2005	71%	29%	0%	7%	93%	0%	100%	0%	100%	0%	100%	0%
2006	68%	32%	0%	6%	94%	0%	100%	0%	100%	0%	100%	0%
2007	66%	34%	0%	5%	95%	0%	100%	0%	100%	0%	100%	0%
2008	64%	36%	0%	4%	96%	0%	100%	0%	100%	0%	100%	0%
2009	62%	38%	0%	4%	96%	0%	100%	0%	100%	0%	100%	0%
2010	60%	40%	0%	3%	96%	0%	100%	0%	100%	0%	100%	0%
2011	58%	42%	0%	3%	97%	0%	100%	0%	100%	0%	100%	0%
2012	55%	45%	0%	3%	97%	0%	100%	0%	100%	0%	100%	0%
2013	53%	47%	0%	3%	97%	0%	100%	0%	100%	0%	100%	0%
2014	51%	48%	0%	2%	97%	0%	100%	0%	100%	0%	100%	0%
2015	50%	50%	0%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2016	48%	51%	0%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2017	48%	52%	0%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2018	49%	51%	1%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2019	49%	50%	1%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2020	50%	49%	1%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2021	51%	48%	1%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2022	52%	46%	2%	2%	98%	0%	100%	0%	100%	0%	100%	0%
2023	53%	45%	3%	2%	97%	1%	100%	0%	100%	0%	100%	0%
2024	53%	43%	4%	2%	97%	1%	100%	0%	100%	0%	100%	0%
2025	53%	41%	5%	2%	97%	1%	100%	0%	100%	0%	100%	0%
2026	53%	39%	7%	2%	96%	1%	100%	0%	100%	0%	100%	0%
2027	53%	38%	9%	2%	96%	2%	100%	0%	100%	0%	100%	0%
2028	53%	36%	11%	2%	95%	2%	100%	0%	100%	0%	100%	0%
2029	53%	34%	13%	3%	94%	3%	100%	0%	100%	0%	100%	0%
2030	52%	32%	16%	3%	94%	4%	100%	0%	100%	0%	100%	0%
2031	51%	31%	18%	3%	93%	4%	100%	0%	100%	0%	100%	0%
2032	51%	29%	20%	3%	92%	5%	100%	0%	100%	0%	100%	0%
2033	50%	28%	22%	3%	91%	6%	100%	0%	100%	0%	100%	0%
2034	49%	27%	24%	3%	90%	7%	100%	0%	100%	0%	100%	0%
2035	48%	26%	25%	3%	89%	8%	100%	0%	100%	0%	100%	0%
2036	47%	26%	27%	3%	88%	9%	100%	0%	100%	0%	100%	0%
2037	46%	25%	29%	4%	87%	10%	100%	0%	100%	0%	100%	0%
2038	46%	24%	30%	4%	86%	11%	100%	0%	100%	0%	100%	0%
2039	45%	24%	32%	4%	85%	12%	100%	0%	100%	0%	100%	0%
2040	44%	23%	33%	4%	84%	12%	100%	0%	100%	0%	100%	0%
2041	43%	23%	34%	4%	83%	13%	100%	0%	100%	0%	100%	0%
2042	42%	22%	36%	4%	82%	14%	100%	0%	100%	0%	100%	0%
2043	41%	22%	37%	4%	81%	15%	100%	0%	100%	0%	100%	0%
2044	41%	21%	38%	4%	80%	16%	100%	0%	100%	0%	100%	0%
2045	40%	21%	39%	4%	79%	17%	100%	0%	100%	0%	100%	0%
2046	39%	20%	40%	4%	78%	18%	100%	0%	100%	0%	100%	0%
2047	39%	20%	41%	5%	77%	19%	100%	0%	100%	0%	100%	0%
2048	38%	20%	42%	5%	76%	19%	100%	0%	100%	0%	100%	0%
2049	37%	19%	43%	5%	75%	20%	100%	0%	100%	0%	100%	0%
2050	37%	19%	44%	5%	74%	21%	100%	0%	100%	0%	100%	0%

The unit price rate of the various fuel types can then be determined from Table 5-13.

Table 5-13 Fuel unit prices (Department for Transport, 2018c)

Fuel and Electricity Prices and Components (2025 prices)						
Year		Resource Cost				
		Petrol	Diesel	Gas Oil	Electricity	
				Rail Diesel	Road	Rail
		(p/litre)	(p/litre)	(p/litre)	(p/kWh)	(p/kWh)
2010		57.74	60.10	53.76	16.11	9.25
2011		70.57	76.28	68.99	17.07	9.59
2012		72.01	78.76	70.97	17.75	10.47
2013		69.53	75.86	68.01	18.54	11.49
2014		61.35	67.25	59.37	18.69	11.64
2015		43.85	47.41	40.22	18.29	11.77
2016		40.65	41.53	36.12	18.00	11.47
2017		48.67	50.80	44.27	18.66	11.93
2018		55.09	59.34	52.28	19.83	11.89
2019		49.24	52.58	45.30	20.62	12.71
2020		43.65	46.31	39.23	19.95	13.54
2021		45.22	48.08	40.96	21.90	14.02
2022		47.48	50.55	43.20	22.30	14.20
2023		48.31	51.49	44.14	22.25	13.82
2024		49.14	52.45	45.11	21.89	13.84
2025		50.01	53.43	46.10	22.12	13.96
2026		51.31	54.93	47.62	22.32	14.02
2027		52.07	55.79	48.51	21.90	13.93
2028		52.81	56.65	49.38	21.84	13.60
2029		53.55	57.49	50.24	21.67	13.45
2030		54.27	58.33	51.08	22.08	13.57
2031		55.49	59.72	52.51	22.02	13.26
2032		56.19	60.53	53.33	21.53	13.14
2033		56.88	61.32	54.13	20.98	12.90
2034		57.56	62.10	54.93	20.68	12.66
2035		58.23	62.86	55.71	20.38	12.57
2036		58.23	62.86	55.71	20.24	12.60
2037		58.23	62.86	55.71	20.19	12.62
2038		58.23	62.86	55.71	20.02	12.80
2039		58.23	62.86	55.71	20.31	12.76
2040		58.23	62.86	55.71	20.00	12.67
2041		58.23	62.86	55.71	20.00	12.67
2042		58.23	62.86	55.71	20.00	12.67
2043		58.23	62.86	55.71	20.00	12.67
2044		58.23	62.86	55.71	20.00	12.67
2045		58.23	62.86	55.71	20.00	12.67
2046		58.23	62.86	55.71	20.00	12.67
2047		58.23	62.86	55.71	20.00	12.67
2048		58.23	62.86	55.71	20.00	12.67
2049		58.23	62.86	55.71	20.00	12.67
2050		58.23	62.86	55.71	20.00	12.67

5.5.2 Consequences of CATs on carriageway aggregate fuel and energy costs

Data analysed for fuel and energy consumption performance for the various scenarios are shown in Figure 5-19.

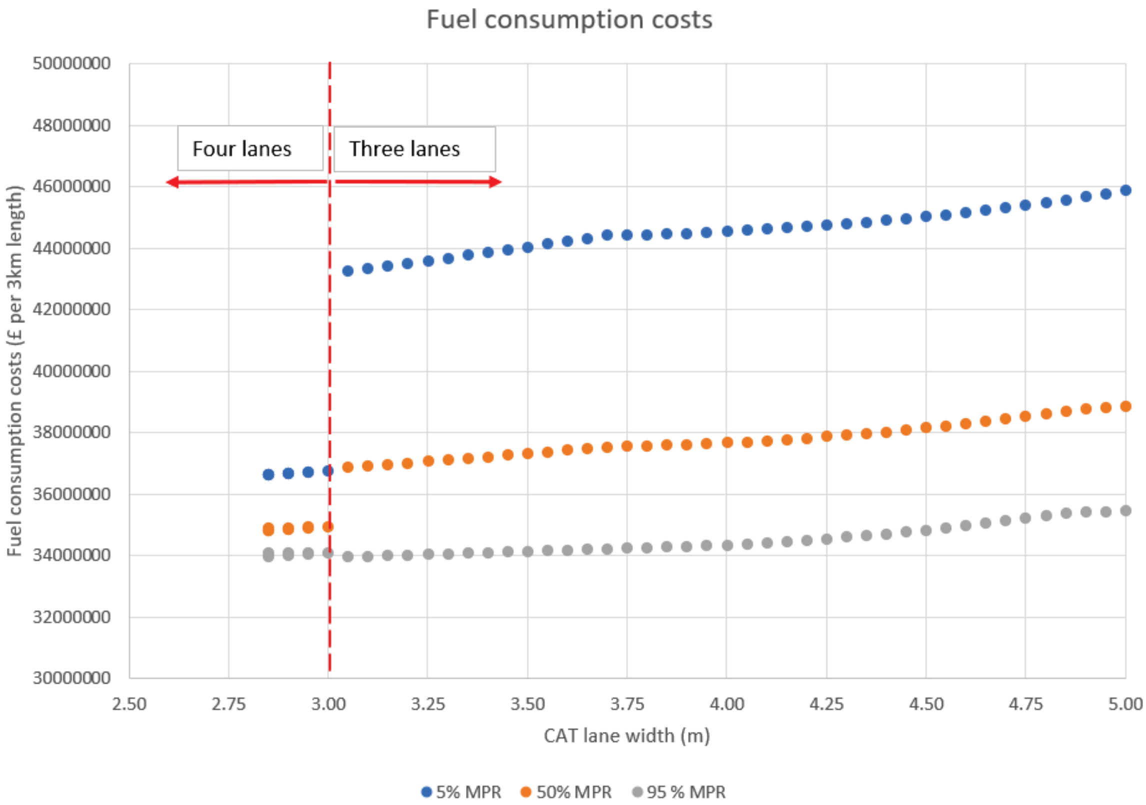

Figure 5-19 Total fuel consumption

Fuel consumption increases with increasing CAT lane width, and similar to travel costs, this is due to having to squeeze manual vehicles within a limited carriageway space when CAT lanes increase. The fuel consumption reduces for increasing MPRs, due to the gains from platooning, where aerodynamic forces on following vehicles are reduced.

The step change in costs from four lane to three lane sections within the low (5%) to medium (50%) MPRs is due to the improved traffic flow as a result of additional capacity from having an additional lane. With the ability to introduce a fourth lane, vehicles travel quicker, and the improved flow enhances the fuel consumption efficiency of the various vehicles.

5.6 Mitigating greenhouse gas emissions through connected autonomous trucks

5.6.1 Approach to quantifying carbon dioxide emissions from CAT-enabled corridors

The amount of CO_2 emissions generated from each cross-section/MPR combination-based scenario was calculated from the fuel consumption amounts, which were determined previously as detailed in Section 5.6 above. Emissions for each of the three energy sources

- diesel, petrol and electricity - was calculated separately as their CO_2 emissions rates differ.

The rates used were derived from Department for Transport's WebTAG, which outline the relationship linking 'fuel burnt' to emissions within its TAG Unit A 3.3.5 (Department for Transport, 2018c). This is reproduced in Table 5-14.

The emissions from each energy source were then summed up to obtain total emissions for each scenario.

Table 5-14 Link between fuel consumed and CO_2e (Department for Transport, 2018c)

Carbon dioxide emissions per litre of fuel burnt / kWh used				
Year	Petrol Kg CO2e/l	Diesel Kg CO2e/l	Gas Oil Rail Diesel Kg CO2e/l	Electricity Roads Kg CO2e/kWh
2010	2.230	2.562	2.926	0.389
2011	2.211	2.567	2.926	0.384
2012	2.211	2.609	2.926	0.377
2013	2.201	2.597	2.852	0.367
2014	2.189	2.601	2.856	0.360
2015	2.189	2.601	2.856	0.350
2016	2.189	2.602	2.856	0.340
2017	2.160	2.556	2.809	0.330
2018	2.130	2.511	2.763	0.319
2019	2.100	2.465	2.716	0.308
2020	2.071	2.420	2.669	0.296
2021	2.071	2.420	2.669	0.283
2022	2.071	2.420	2.669	0.269
2023	2.071	2.420	2.669	0.255
2024	2.071	2.420	2.669	0.240
2025	2.071	2.420	2.669	0.224
2026	2.071	2.420	2.669	0.207
2027	2.071	2.420	2.669	0.189
2028	2.071	2.420	2.669	0.171
2029	2.071	2.420	2.669	0.151
2030	2.071	2.420	2.669	0.130
2031	2.071	2.420	2.669	0.105
2032	2.071	2.420	2.669	0.085
2033	2.071	2.420	2.669	0.069
2034	2.071	2.420	2.669	0.056
2035	2.071	2.420	2.669	0.045
2036	2.071	2.420	2.669	0.036
2037	2.071	2.420	2.669	0.029
2038	2.071	2.420	2.669	0.024
2039	2.071	2.420	2.669	0.019
2040	2.071	2.420	2.669	0.016
2041	2.071	2.420	2.669	0.013
2042	2.071	2.420	2.669	0.012
2043	2.071	2.420	2.669	0.012
2044	2.071	2.420	2.669	0.011
2045	2.071	2.420	2.669	0.010
2046	2.071	2.420	2.669	0.009

In addition, the monetary value of the carbon dioxide emissions are also used to determine the cost. Again, this was derived from the mid-range figures of the value of carbon dioxide emissions presented within WebTAG, reproduced in Table 5-15.

Table 5-15 Monetary value of CO_2e (Department for Transport, 2018c)

Non Traded Values, £ per Tonne of CO2e (2025 prices)			
Year	Low	Central	High
2010	112.55	225.10	337.65
2011	114.27	228.53	342.80
2012	116.01	232.01	348.02
2013	117.77	235.54	353.32
2014	119.57	239.13	358.70
2015	121.39	242.77	364.16
2016	123.24	246.47	369.71
2017	125.11	250.22	375.34
2018	127.02	254.03	381.05
2019	128.95	257.90	386.85
2020	130.92	261.83	392.75
2021	133.37	266.74	400.11
2022	135.40	270.80	406.20
2023	137.46	274.92	412.39
2024	139.56	279.11	418.67
2025	141.68	283.36	425.04
2026	143.84	287.68	431.51
2027	146.03	292.06	438.09
2028	148.25	296.50	444.76
2029	150.51	301.02	451.53
2030	152.80	305.60	458.41
2031	155.13	310.26	465.39
2032	157.49	314.98	472.47
2033	159.89	319.78	479.67
2034	162.32	324.65	486.97
2035	164.80	329.59	494.39
2036	167.31	334.61	501.92
2037	169.85	339.71	509.56
2038	172.44	344.88	517.32
2039	175.07	350.13	525.20
2040	177.73	355.46	533.20
2041	180.40	360.80	541.20
2042	183.10	366.21	549.31
2043	185.85	371.70	557.55
2044	188.64	377.28	565.92
2045	191.47	382.94	574.41
2046	194.34	388.68	583.02

5.6.2 Results of carbon dioxide emissions calculation

The results for CO_2e costs are shown in Figure 5-20. The graphs follow a very identical trend to the fuel consumption curves, including the step changes from 3m to 3.05m wide CAT lane width, when the section changes from four lanes to three lanes. This is because the energy savings from platooning detailed in Section 5.6 above also translates proportionally to reductions in CO_2 emissions.

Typically, an increase in CAT lane width results in an elevation of CO_2e levels, as manual vehicles – which form a large proportion of the total vehicle fleet - are compelled to navigate a restricted carriageway when the CAT lanes widen. Conversely, an increase in

MPRs leads to a decrease in emissions due to the benefits accrued from platooning, which reduces aerodynamic drag on the trailing vehicles.

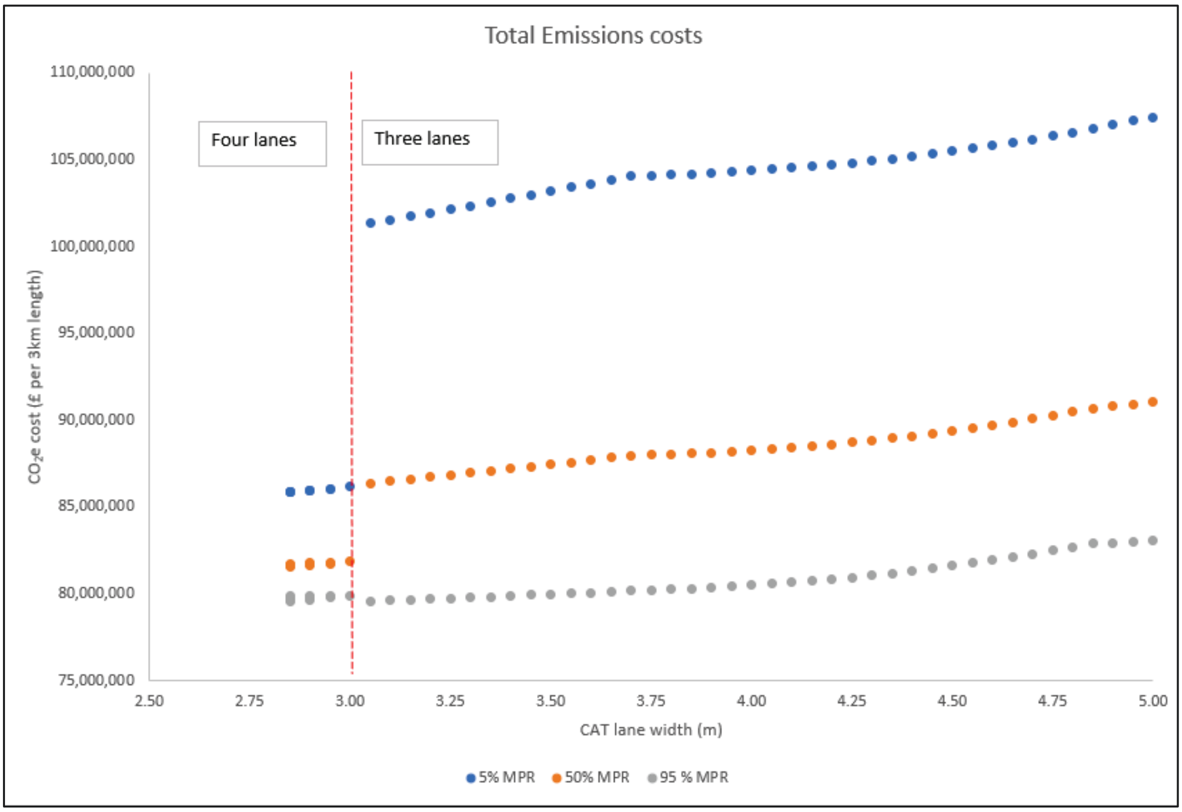

Figure 5-20 Total emissions

5.7 Travel time costs, evaluating delays from CAT-induced disruptions

The travel time cost relates to the value of time for traversing the case study section. This occurs under three different conditions:

- Travelling under temporary traffic management during initial conversion
- Travelling under temporary traffic management during maintenance
- Travelling during normal, permanent operations.

The time it takes to travel is affected by lane widths, number of lanes, and MPR.

5.7.1 Travel time during normal operations

The time taken to travel during normal operations is affected by mandatory speed limits, lane widths, and volume/capacity ratios.

5.7.1.1 Effective free-flow speeds

The various alternatives have varying lane widths and, and this will affect free flow speeds. To calculate the total travel time taken by manual vehicles, firstly, effective free-flow speeds are calculated. These are the speeds that vehicles would travel at based on lane widths and limited by the mandatory speed limit. Linear regression models were developed for calculating the effective free-flow speeds for manual trucks (MTs) and Passenger Cars (PCs) by analysing data on the relationship between cross-section widths and speeds. The data was obtained from other studies (Chitturi and Benekohal, 2005).

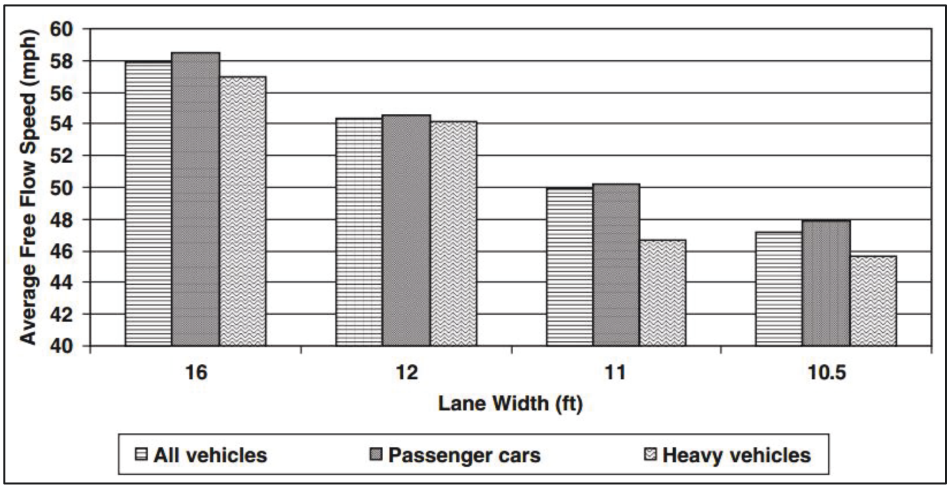

Figure 5-21 Free-flow speed variation with lane width (Chitturi and Benekohal, 2005)

The regression models derived from Figure 5-21 are shown in Figure 5-22 and Figure 5-23. The data points for the PCs excluded the 16ft (circa 4.90m) wide lane. This is because, the PC lane is limited to 3.65m maximum in this research, and so a more accurate and representative regression model should exclude wider lanes.

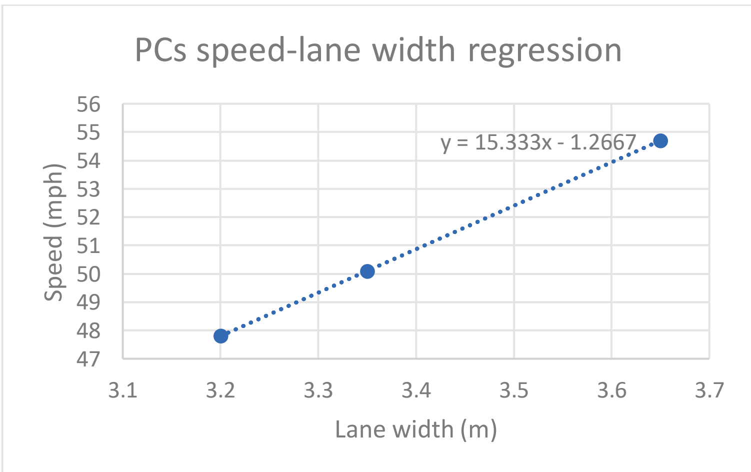

Figure 5-22 Model for PCs Free-flow speed variation with lane width

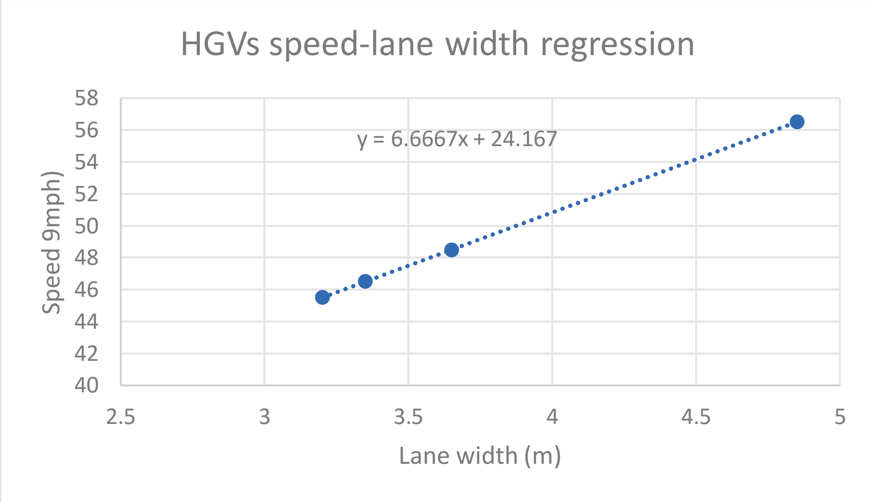

Figure 5-23 Model for HGVs Free-flow speed variation with lane width

To calculate the total travel time taken by manual vehicles, firstly, effective free-flow speeds are calculated. These are the speeds that vehicles would travel at based on lane widths and limited by the mandatory speed limit. Linear regression models were developed for calculating the effective free-flow speeds for manual trucks (MTs) and Passenger Cars (PCs) by analysing data on the relationship between cross-section widths and speeds. The data was obtained from other studies (Chitturi and Benekohal, 2005). The models obtained are shown in these equations:

$$EFFS_{PC} = 15.333(Lane_{PC}) - 1.2666 \qquad \text{Equation 5-8}$$

$$EFFS_{MT} = 6.6667(Lane_{MT}) + 24.167 \qquad \text{Equation 5-9}$$

Where:

$EFFS_{PC}$ and $EFFS_{MT}$ are the effective free-flow speeds for PC and MT in mph, respectively, $Lane_{PC}$ and $Lane_{MT}$ are the lane widths for PC and MT, in m.

CAT, however, were taken as travelling at posted speeds, irrespective of lane widths, due to the reduced influence of human behaviour.

5.7.1.2 Demand distribution and capacity analysis

Speeds (and by extension, journey times) are also influenced by traffic volumes (demand) and capacity of the roadway; and these in turn are impacted by the number of lanes and distribution of vehicles across these lanes.

For the MV, maximum capacity is then taken as 1900 pcu/hr/lane (Yousif, 2002). This was then doubled to 3800 pcu/hr/lane capacity for CATs, as headways for autonomous vehicles in platoon situations are expected to be half that of MV (Mohajerpoor and Ramezani, 2019). Passenger car unit values estimation methods was then used to convert HGVs to pcu equivalents (Transport for London, 2021).

The Average Annual Daily Traffic (AADT) is converted to individual hourly flow volumes using standard hourly traffic profiles, depicted in Figure 5-24 (Havaei-Ahary, 2022).

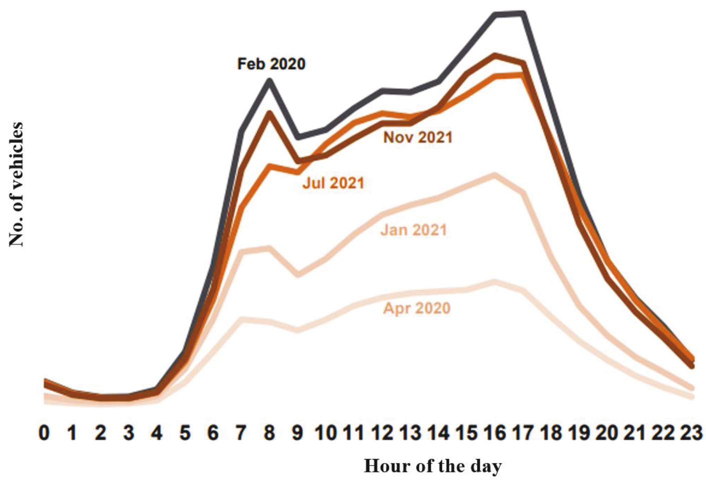

Figure 5-24 One-day vehicle flow profile. Taken from Havaei-Ahary (2022)

Secondary models were then applied to predict the distribution of manual vehicles across the multi-lane cross-section. For the 4-lane cross-section scenarios, because the outermost lane is designated a CAT lane, the manual vehicles for the 3 manual lanes are distributed using the models developed in Germany by Ruhr University (Wu, 2006). Similarly, for the 3-lane cross-sections, the distribution was based on British 2-lane motorway models (Yousif et al., 2013).

The key assumptions for the CAT lane are that:

- CAT maintain 100% lane discipline and stay within the dedicated lane.
- CAT travel at exactly the posted speed limit
- MVs do not encroach within the CAT lanes
- CAT lane is not affected by lane widths

5.7.1.3 Travel delay evaluation

The actual journey times during normal operations were calculated using the US Bureau of Public Roads (BPR) travel delay function (Horowitz, 2009):

$t = t_o(1 + \alpha X^{\beta})$ Equation 5-10

Where:

t is travel delay, in hour

t_o is the travel time during effective free-flow conditions, in hour

X is the volume-to-capacity ratio, hence is dimensionless.

α and β are empirical coefficients that depend on the road class and speed limit.

5.7.1.4 Value of time for normal operations

Once the time delay was determined, time cost rates by vehicle type was obtained from WebTAG and used to calculate travel time costs (Department for Transport, 2018c). Being conscious that the WebTAG values are for manual vehicles only, rate for CAT were derived as being a third of the rate for manual trucks on the basis that average platoon size is three, requiring one driver for three trucks; the two drivers in the following trucks can rest or engage in other economic activity during platooning.

This is considered a reasonable estimate, because while it may be seen as a conservative estimate because no driver intervention is expected for fully autonomous vehicles, drivers 'resting' in the cab are limited in the type of economic or leisure tasks they can engage in, hence will not be fully utilised economically.

The monetary value of time used in the analysis is calculated from Table 5-16.

Table 5-16 Vehicle values of time (Department for Transport, 2018c)

Table A 1.3.5: Market Price Values of Time per Vehicle based on distance travelled (£ per hour, 2025 prices and 2025 values)

Vehicle Type	Journey Purpose	Weekday					Weekend	All Week
		7am – 10am	10am – 4pm	4pm – 7pm	7pm – 7am	Average		
Car	Work	31.39	32.17	31.84	32.45	31.90	36.46	32.22
	Commuting	17.69	17.98	17.75	18.01	17.81	18.86	17.90
	Other	12.21	13.00	12.78	12.74	12.77	15.12	13.60
	Average Car	17.78	16.75	17.08	17.31	17.18	16.15	16.94
LGV	Work (freight)	23.58	23.58	23.58	23.58	23.58	24.76	23.58
	Commuting & Other	14.00	14.00	14.00	14.00	14.00	19.47	15.25
	Average LGV	22.43	22.43	22.43	22.43	22.43	24.12	22.58
OGV1	Working	22.66	22.66	22.66	22.66	22.66	22.66	22.66
OGV2	Working	22.66	22.66	22.66	22.66	22.66	22.66	22.66
PSV (Occupants)	Work	24.96	25.48	26.69	26.67	25.69	23.33	25.11
	Commuting	35.14	12.31	49.42	67.55	30.49	11.55	25.82
	Other	69.75	79.93	62.45	54.18	71.54	81.25	73.94
	Total	129.84	117.73	138.56	148.40	127.72	116.14	124.86

For instance, from Table 5-16, HGV value = Average (OGV1, OGV2, PSV) = Average (22.6, 22.6, 124.86) = £56.72/hr.

5.7.1.5 Travel time during temporary traffic management (TTM)

During both initial conversion and in-operation maintenance, TTM would need to be installed. This causes disruption to the network. Two pavement rehabilitation cases were considered: CAT and manual truck lane rehabilitations. Lanes used solely or predominantly by lighter vehicles were discounted, as they impose negligible pavement damage.

There have been many studies recently regarding impact and performance of CAVs at road works (Pourfalatoun and Miller, 2021, Abdulsattar et al., 2020, Liu et al., 2019, Adomah et al., 2021). However, these are based on the standard cross-section lane width for the normal operation scenario to start width. And they also do not include a calculation for the effect of frequency of pavement rehabilitation that needs to be carried out.

For this study, temporary manual vehicle lanes were designed using industry guidance (Gregg, 2007); temporary lanes for CATs employed innovative solutions that relied on the increased wheel tracking capabilities and anticipated compliance to speed limits. Designs for temporary cross-sections and layouts during pavement rehabilitation works were then undertaken using AutoCAD, a 3-dimensional civil engineering design software that increased accuracy and efficiency of the design process. The design intent was to provide sufficient working area and safety buffer zones, and then apply appropriate temporary reduced mandatory speed limits. Temporary lanes generally followed the existing permanent road markings, to avoid confusion caused by ‘ghost markings’ where original markings remnants are visible (Alzraiee et al., 2021). All the TTM options used lane closures and narrow lanes, with no road closures/diversions.

The basis for designing these TTM sections are as follows:

- Provide sufficient working area. For a lane that requires rehabilitation, the full width of the lane is closed off and used as the working area. This will enable all necessary construction equipment to access and move safely within the work area.

- Provision of safety zone between working area and temporary running lanes. 1.2m is generally provided, with the adjacent running lane limited to a temporary mandatory speed limit of 50mph. However, where the 1.2m separation was not achievable, 0.5m safety zone was provided, and the temporary mandatory speed limit reduced to 40mph.

- The aspiration was to provide as many traffic lanes as possible to minimise the delays. However, the absolute minimum lane width of 2.40m (for passenger cars) was implemented. This resulted in instances where one wide lane was shared by all manual vehicles (manual trucks and passenger cars), rather than provide a very narrow car lane and a manual truck lane.

The TTM designs are illustrated in Figure 5-25 and Figure 5-26.

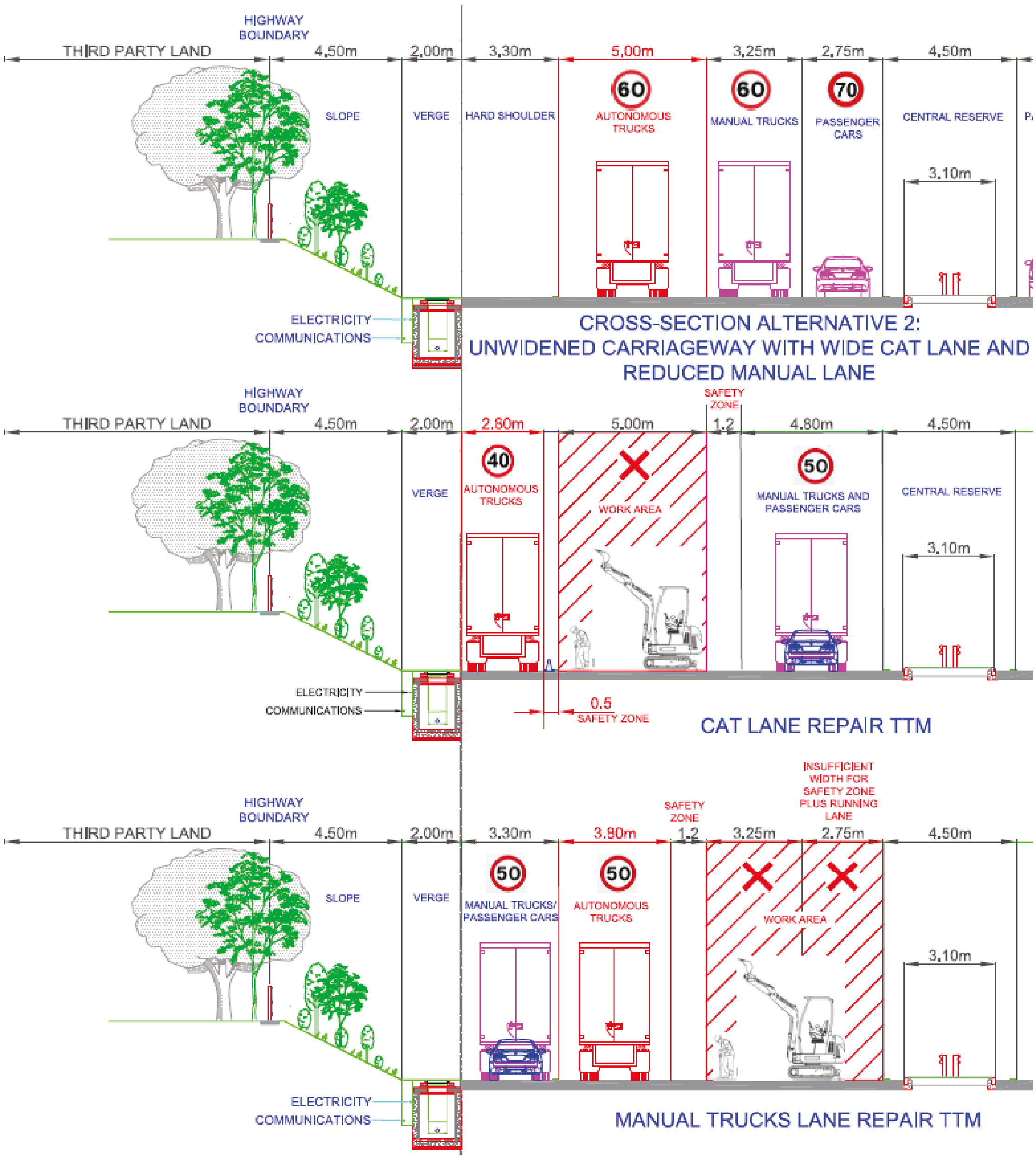

Figure 5-25 TTM for 3-lane cross-section

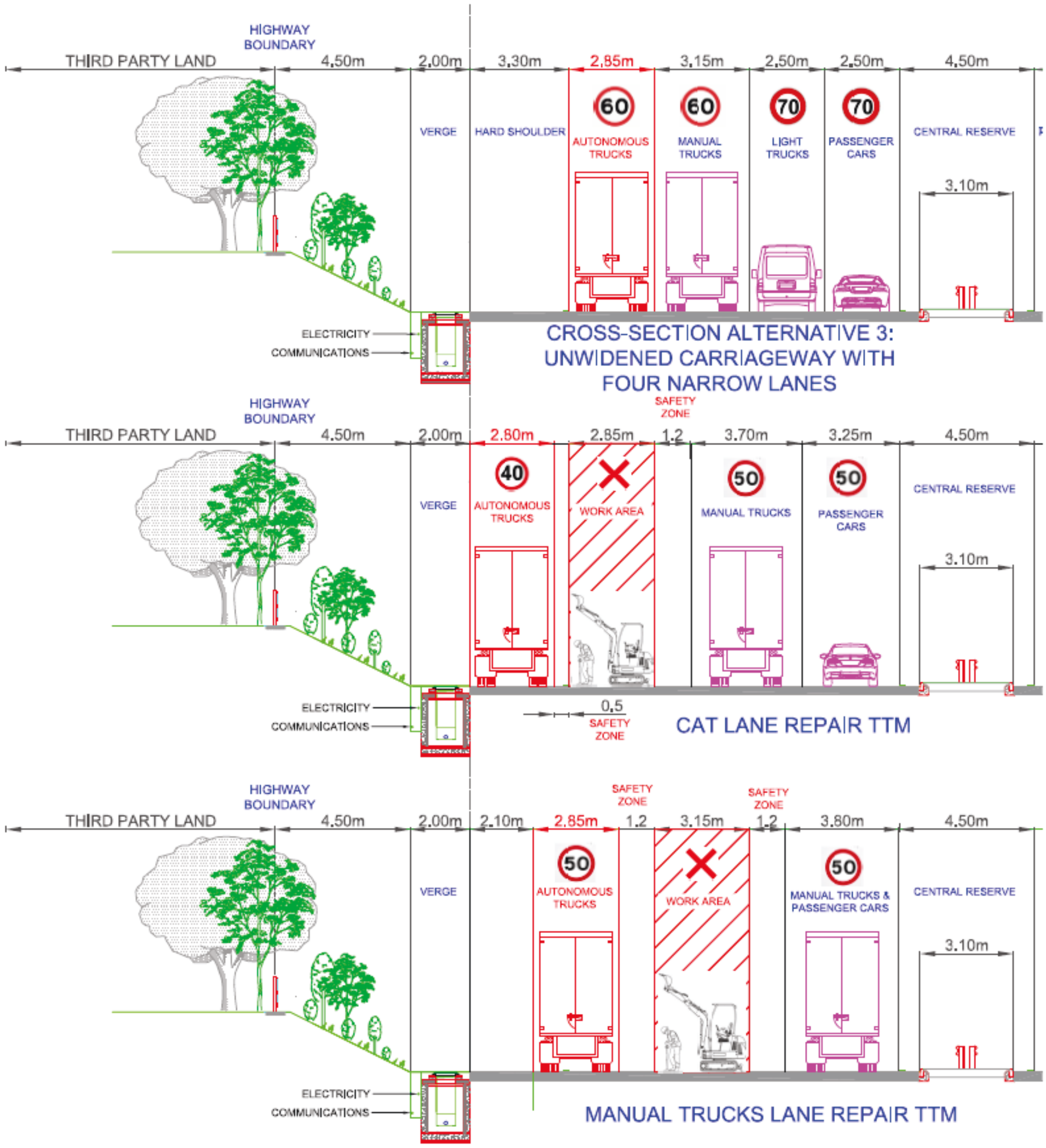

Figure 5-26 TTM for 4-lane cross-section

Time delays experienced each day during TTM were calculated using the methodologies described in Section 5.8.1 above. To determine the total delay, the total duration (or number of days) that TTM was in place had to be calculated, using the Bromilow Time-Cost (BTC) model (Kaka and Price, 1991). The model was developed through empirical research and mathematical modelling, integrating concepts from project management, operations research, and cost analysis to address time-cost trade-offs in construction projects. This is a linear regression relationship of the form:

$$T = k \cdot C^{\beta} \quad \text{Equation 5-11}$$

Where:

T is the construction (or conversion) time (in working days), C is the construction value, or the cost of the rehabilitation (in £m), and k and B are constant coefficients. For this research, the study section is categorised as a major highway project, and this corresponds to values of $k = 258.1$ and $\beta = 0.469$.

The BTC provides a systematic framework for evaluating the effects of project duration on project costs and vice versa. In civil engineering construction practice, it serves as a decision-making tool to optimize project schedules considering both time and cost constraints, and is based on the principle that there exists a relationship between project duration and project cost, affording the opportunity for time-cost trade-off.

In summary, the installation of Temporary Traffic Management (TTM) will be required during conversion and maintenance for the innovative, CAT-enabled cross-section alternatives. This causes disruptions to the network to different degrees, and this can be measured using the Bromilow Time-Cost model to provide insights into the time and cost implications of TTM. This will contribute to the understanding of TTM implementation and can assist in decision-making for future construction and maintenance projects for highways designed for autonomous vehicles.

5.7.2 Travel time costs results and discussion

The results of the analysis involving total costs due to the economic value of travel time are shown in Figure 5-27.

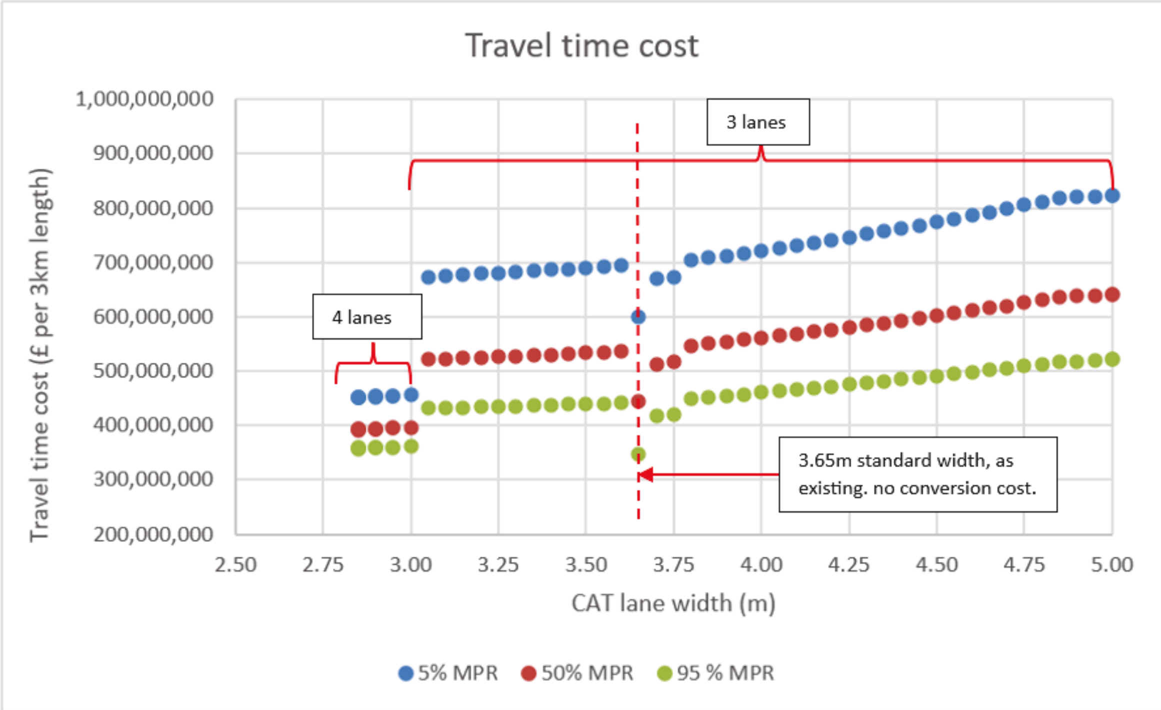

Figure 5-27 Value of travel time

Travel time cost generally increases with increasing CAT lane width. This is because, as CAT lane increases, there is a reduced carriageway width available for the manual vehicles, which must fit into a narrower space. The exception is for having a standard lane width of 3.65m, and this is because, for this scenario, there is no travel disruption cost during the initial conversion as the existing highway configuration is maintained. This explains why, for all MPR values, there is a sharp drop at 3.65m CAT lane. The premise of the analysis is that CAT actual speeds are unaffected by lane widths, so there is no travel time gains for the wider CAT lanes.

There is a significant drop in travel time cost for very narrow CAT lanes (≤ 3m), because this allows two PC lanes to be fitted within the carriageway, thereby creating a four lane configuration which significantly improves traffic flow, given that most vehicles are PCs.

Travel time cost generally decreases within increasing MPRs. This is because CATs are more likely to travel closer to the desired speeds. Also, increased number of CATs imply reduced driver costs due, as platooning will reduce number of drivers required, and/or allow drivers to engage in economic activities will ‘driving’.

5.8 Summary of whole-life costing approach to multi-scenario analysis for connected autonomous vehicles

The initial task was to gauge how CAVs could affect the performance of highways. This was achieved through broad engagement in expert CAV communities. This understanding, complemented by a review of existing research, facilitated the formulation of scenarios, which were then comparatively analysed for their whole-life cycle performance. The scenarios involved modifying an existing standard conceptual motorway section. The design of the cross-section alternatives resulted in 50 different cross-sections. Coupled with 11 MPRs, a total of 550 different scenarios were developed and analysed.

Subsequently the costs associated with the different options for constructing dedicated CAT lanes, as well as the costs of maintaining and operating these lanes are calculated. Firstly, the conversion costs for each modification option were calculated. In the subsequent steps, the study combined multiple discrete mathematical transport models by establishing a complex interlinked network of relationships where outputs are successively caried through and used as inputs in the subsequent stages. These models were originally developed for conventional manual vehicles, thus required adaptations specifically for this study to align with the unique characteristics of CAVs. To achieve this, the modifications were informed by secondary data derived from prior studies on CAVs.

Pavement, one of the most importation infrastructural components of the highway system, was analysed using a bespoke software programme. Industry standards and guidance documents on roadworks safety were used in modelling temporary road layouts during construction and maintenance.

As an overview, the methodology utilised in determining the whole life cost components is presented in the flowchart in Figure 5-28.

Item	Descriptions and/or References
MPRs	Market Penetration Rates
DfT TSM Ch 8	Department for Transport, Traffic Sign Manual Chapter 8 - Traffic Safety Measures and Signs for Road Works and Temporary Situations (Gregg, 2007).
TxME	Texas Mechanistic-Empirical Asphalt Concrete Pavement Design & Analysis System (Hu et al., 2013).
ReCAP	Research for Community Access Partnership (Pinard and Hongve, 2020).
SPON's	Spon's Civil Engineering and Highway Works Price Book (AECOM, 2021).
HCM	Highway Capacity Manual. Models interpretations by Horowitz (1991).
BTC	Bromilow Time-Cost model (Kaka and Price, 1991).
Lane Utilisations	Demand distribution and capacity analysis models by Wu (2006) and Yousif et al. (2013).
Chitturi	Lane/speed models by Chitturi and Benekohal (2005).
WebTAG	Web-based Transport Analysis Guidance (Department for Transport, 2018c).

Figure 5-28 Summary of approach to calculating various whole-life cost components

Chapter 6 WHOLE-LIFE COST ANALYSIS FOR AUTONOMOUS TRUCK-ENABLED HIGHWAYS

6.1 Results analysis and discussion of whole-life cost variability

The various individual costs over the design life of the road were then summed up to obtain a total Whole-life cost (WLC). Appendix A displays the breakdown of the separate costs and the total whole-life costs.

The WLC data was then analysed, as shown in Figure 6-1.

It can be observed that whole-life cost follows a similar trend to the travel cost discussed in Section 5.8.2 above, in that WLC increases with increasing CAT lane width and decreases with increasing MPR. The reason is that travel cost is the clear dominant component in the measurement of WLC, due to differences in the order of magnitude of the component costs. Whereas initial conversion cost is in the hundreds of thousands for initial conversion, maintenance cost is in the millions, with safety, fuel consumption and carbon dioxide emissions costs falling within the tens of millions. Travel costs, however, falls within the hundreds of millions.

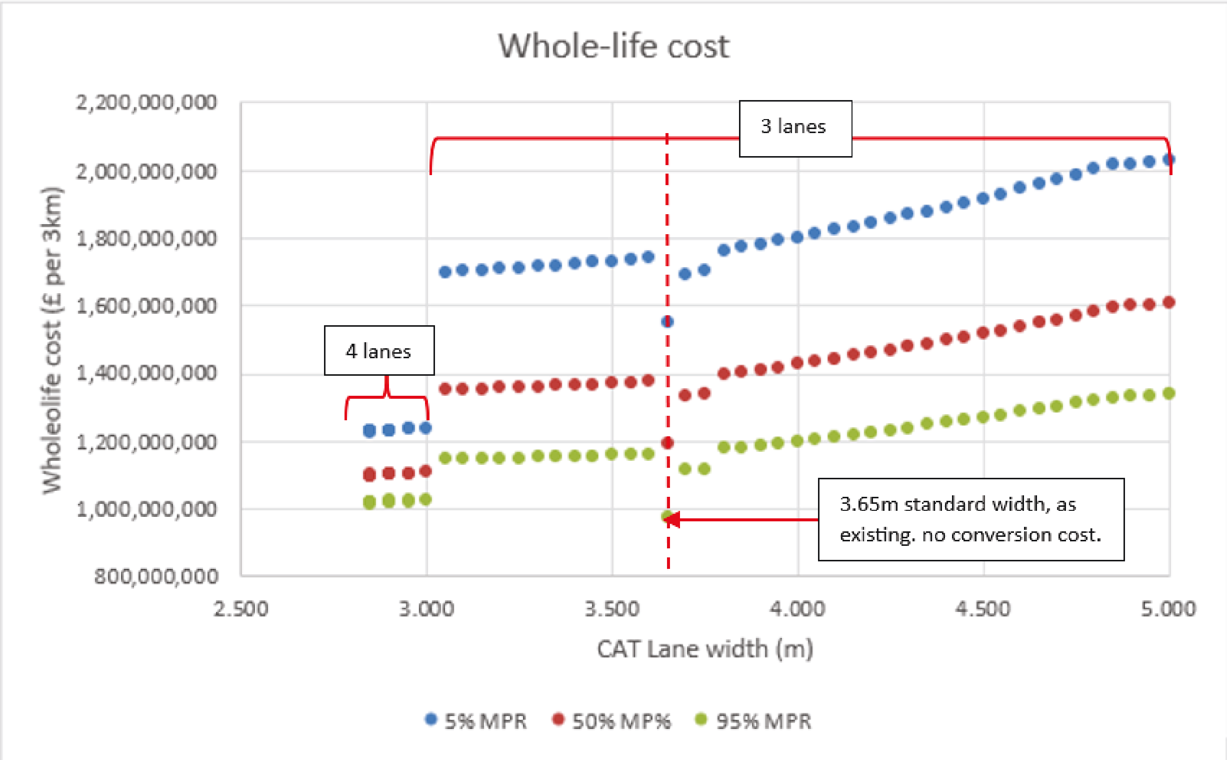

Figure 6-1 Two-way whole-life costs per 3km section

6.2 Towards development and validation of a multiple linear regression model for whole-life cost prediction

This section highlights the application of statistical diagnostic tests, the selection of validated variables, and the development and interpretation of a multiple linear regression model for assessing whole-life cost. The whole-life cost components are made up of several dozen terms, hence developing a linear model enables the research results to be reported in a more easily accessible format.

6.2.1 Application of statistical diagnostic test as assurance mechanism for regression model validity and reliability

In this sub-section the application of statistical diagnostic tests as an assurance mechanism for regression model validity and reliability is presented. The steps taken to ensure the validity and reliability of the statistical analyses performed in relation to the regression model are outlined.

6.2.1.1 Justification and application of multicollinearity diagnostic test

A multicollinearity test was performed on the input variables. This diagnostic test was carried out to ensure that the level of correlation among the variables was low enough to provide a stable regression model. A stable regression model is important as it confirms that the model's coefficients are reliable and that the model's predictions are consistent across different datasets. This stability is critical for the model's generalisability and reliability in predicting whole-life costs accurately.

Although the values were predetermined, collinearity can affect the stability and interpretability of the regression coefficients. Ensuring low collinearity is important to maintain the robustness of the model. The modelling is based on the same of the individual lanes always being equal to 11m, and there could have been high collinearity between the lane widths as increasing one leads to reduced space for the others.

Multicollinearity test was considered sufficient and the most relevant for this study due to the nature of the three cross-section variables: the sum of all the lane widths had to be the same (11m) in all scenarios. Hence this test would provide a measure of the regression model's reliability.

6.2.1.2 Multicollinearity results: correlation coefficients interpretation and analysis

The results of the multicollinearity tests provided in Table 6-1 are the correlation coefficients among the variables in the dataset. Specifically, the table shows the pairwise correlation coefficients between the six variables, i.e., Lane 1 (CAT Lane), Lane 2 (MT Lane), Lane 3 (PC Lane 1), Lane 4 (PC Lane 2,) MPR (%), and WLC. The diagonal entries show the correlation between each variable with itself, which is always 1.

Table 6-1 Correlation coefficients among variables

	Lane 1: CAT Lane	Lane 2: MT Lane	Lane 3: PC Lane 1	Lane 4: PC Lane 2	MPR (%)	WLC
Lane 1: CAT Lane	1.00000					
Lane 2: MT Lane	0.220189	1.00000				
Lane 3: PC Lane 1	-0.20225	0.766151	1.00000			
Lane 4: PC Lane 2	-0.65688	-0.84098	-0.58616	1.00000		
MPR (%)	0.00000	0.00000	0.00000	0.00000	1.00000	
WLC	0.61312	0.380858	0.075182	-0.57785	-0.70161	1.00000

The table shows that there is some degree of correlation among the variables. The correlation coefficient between Lane 1 (CAT Lane) and Lane 2 (MT Lane) is 0.220189, indicating a weak positive correlation between these two variables. Similarly, there is a weak negative correlation between Lane 1 and Lane 3, with a correlation coefficient of -0.20225.

Overall, the inter-correlation coefficient among the paired variables of Lane 1 (CAT Lane), Lane 2 (MT Lane) and MPR are weak, indicating negligible or no correlation between these variables. Therefore, including these variables in a linear regression model would not cause multicollinearity issues.

Worthy of note is that the correlation coefficient between MPR (%) and all other input variables is 0, indicating that there is no correlation between MPR (%) and the other independent variables.

Except for Lane 3 (which has a weak positive correlation coefficient of 0.075182 with WLC), the correlation coefficient between WLC and the other cross-sectional variables is relatively high (0.38086 to 0.61312). This indicates a substantial positive correlation between WLC and the cross-section. This provides increased confidence for the regression relationship derived.

6.2.1.3 Selection of validated variables using multicollinearity

Based on the correlation coefficients among the five input variables and the dependent variables, the variables that would provide the best predictive power for a multiple linear regression model are CAT Lane, MT Lane and MPR. A table showing the correlation coefficients of these variables is shown in Table 6-2; the weak inter-correlation coefficients among the three variables indicating the strong predictive power for the regression model.

Table 6-2 Multicollinearity analysis of variables

	Lane 1: CAT Lane	Lane 2: MT Lane	MPR (%)	WLC
Lane 1: CAT Lane	1.00000			
Lane 2: MT Lane	0.22019	1.00000		
MPR (%)	0.00000	0.00000	1.00000	
WLC	0.61312	0.38086	-0.70161	1.00000

6.2.2 Multiple linear regression modelling

The focus of this section is on multiple linear regression modelling, including background information, analysis, discussion on statistical parameters and the interpretation of the derived model.

6.2.2.1 Background and general information

Regression analysis was conducted on the 550 observations to determine a mathematical model for whole-life cost.

The result of this analysis is shown in Table 6-3, and represents a multiple linear regression model that relates whole-life cost as the dependent variable to three validated independent variables.

Two of these validated variables are related to the cross-section widths (Lane 1: CAT Lane and Lane 2: MT Lane), with market penetration rate (MPR) being the other input variable.

6.2.2.2 Examination of the regressor-response variable relationship

There is a very strong positive correlation between the dependent variable and the independent variables, as demonstrated by the value of the multiple correlation coefficient (R) being 0.9652.

Also, the R-squared value (0.9317) means that the model explains over 93% of the variation in the dependent variable. This indicates that a very high proportion of the variation in whole-life cost among the scenarios is explainable by the cross-section and MPR values. Hence the model is a good fit for the data and can be effectively used to predict the regressor values.

As the adjusted R-square of 0.9313 is slightly lower than the R-square value, it implies the mathematical model obtained by regression analysis is adequately refined, so expanding the scenarios and independent variables would not improve the predictive precision. The 550 observations, therefore, is a sufficiently large and varied sample space for this simulation.

6.2.2.3 ANOVA, Coefficients and Statistical Significance

The ANOVA table shows that the regression model is statistically significant, with an F-value of 2483 at a significance level of zero, which is less than 0.05. This implies that the independent variables are a significant predictor of the dependent variable.

The extent to which each of these input variable affects the whole-life cost is presented in the column for coefficients in Table 6-3.

MPR is negatively correlated to the regressor variable, while both CAT and MT lane width variables are positively correlated to whole-life costs. This is consistent with the findings in Chapter 5, where the conclusion was that increasing the lane widths for CAT and MT meant very narrow lanes for passenger cars, which increased their travel time significantly and caused congestions, as they slow down to compensate for the increased psychological load of driving in reduced lane widths. PCs form about 90% of vehicle mix for typical trunk road traffic, hence their travel time costs have a considerable influence on overall cost.

By contrast, higher MPRs improved traffic flows and reduced vehicle operation costs (fuel consumption, carbon dioxide emissions and accidents), thereby bringing down the overall costs.

All the three independent variables use in the regression modelling have p-values of zero (to four decimal places), indicating that they are all statistically significant.

6.3 Optimal solutions: mathematical model derivation and interpretation

Figure 6-1 shows a general linear relationship. The exception is sharp drop in costs when the CAT lane is 3m width or narrower, and another sharp drop when the CAT lane is 3.65m wide. In the former situation, the very narrow CAT lane enables four lane configurations, which enables free traffic flows for the manual vehicles, hence reducing travel time cost significantly. In the latter case, the standard 3.65m lane is retained as existing, hence no initial conversion cost or conversion induced travel time disruption, is incurred.

For situations when the CAT lane (Lane 1) is between 3m and 5m (but ≠ 3.65m), the multiple linear regression model that relates the whole-life cost as the dependent variable to four independent variables, as derived from the regression analysis is shown as:

$$W = 2.16 \times 10^{8} + 2.05 \times 10^{8}(\text{Lane 1}) + 1.94 \times 10^{8}(\text{Lane 2}) - 5.87 \times 10^{6}(\text{MPR})$$

Equation 6-1

The intercept term is approximately 216,000,000, which is comparable or higher than the input parameter coefficients. However, this carries little practical application as the independent variables in the model are physical features that cannot be zero (the lanes must be present with non-zero positive values as part of the road).

Inspecting the equation and the signs of the coefficients, the optimal (minimal) cost will occur when both CAT and Manual lanes are as low as possible, with the MPR as high as possible.

For CAT Lane = 3.65m (see

Table 6-5);

$$W = 1.54 \times 10^9 - 6.37 \times 10^6 (MPR) \qquad \text{Equation 6-2}$$

Under this condition, the lowest cost occurs when MPR is highest. The CAT lane width remains constant at 3.65m, and is not included as an independent variable in this model.

Finally, for CAT lane ≤ 3.00m (See

Table 6-5):

$$W = 9.18x10^8 + 7.73x10^7(Lane\ 1) + 2.82x10^7(Lane\ 2) - 2.31x10^6(MPR) \qquad \text{Equation 6-3}$$

The again, the lowest cost under this circumstance will be when CAT and MT lanes are both as low as possible, and the MPR value is at its maximum.

For the optimisation constraints, the minimum CAT lane width is limited by the physical space requirements of the largest (widest) design vehicle plus allowance for some wander and aerodynamic effects. This is taken as 2.85m for the research.

The minimum MT and PC lanes are constrained by narrow lanes permitted in temporary traffic situations from design guidance. Minimum MT lane is taken as 3m, while minimum PC lane is 2.5m.

Although the MPR is included as a variable within the equations, this parameter is most likely to be driven by consumer behaviour with regards to uptake of connected autonomous vehicles, as well as legislation enabling integration of CATs. It is not likely to be within the control of highway engineers. However, as the particular optimised model is likely to depend on CAV penetration rates, this is necessary to include this as a variable, as that optmised designs can be tailored to traffic conditions. The inclusison of MPR as a decision variable in the mathematical models is analogous to how traffic volumes – which is an exogenous variable outside highway engineers' control – influences road cross-section designs.

6.3.1 Low to mid-range MPR

When MPR is low to mid-range, the optimal design is to install narrow, sub-standard CAT and MT lanes of 2.85m and 3m, respectively. This design will leave sufficient space to install two PC lanes, each 2.575m wide, retaining the existing 11m total carriageway width. The optimal cross-section under this circumstance, therefore, is a non-standard four-lane configuration. The remodelling of the base case to produce this optimised cross-section design for connected autonomous trucks is shown in Figure 6-2.

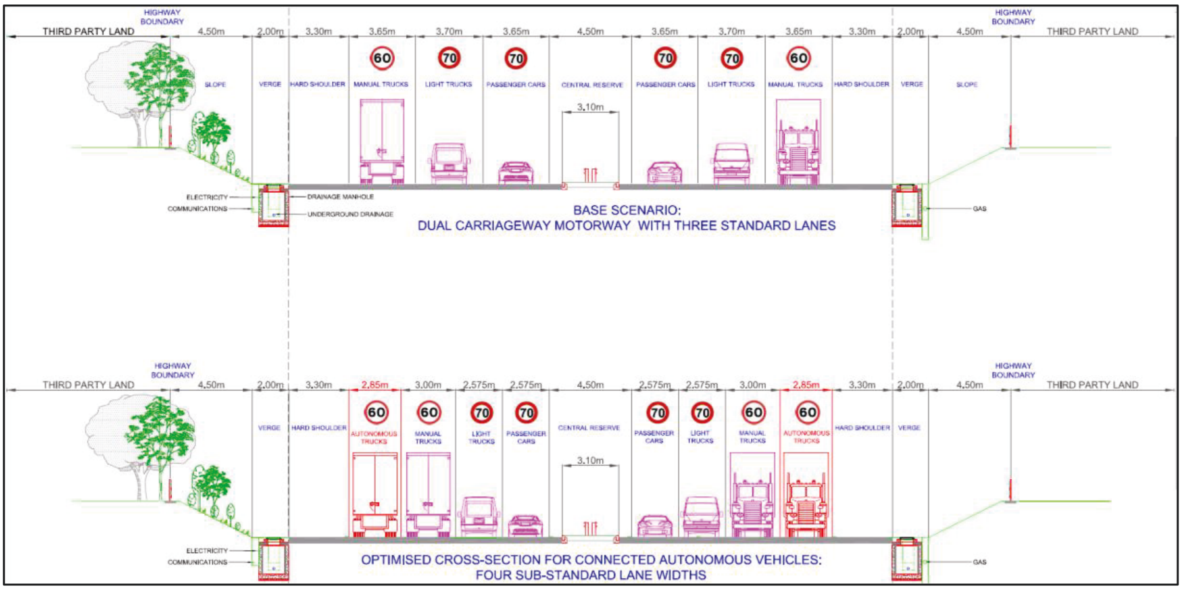

Figure 6-2 Optimised cross-section very low to mid-range MPR)

Although narrow lanes widths have been found to adversely affect capacity and safety, with the introduction of CATs, some of the HGVs will be occupying only the CAT lane, and the manual lanes can be feasibly operated as narrow lanes. This assertion is partially supported by a study on reduced lane widths (minimum widths of 3m) at motorway roadworks, which found that the presence of HGVs led to driver re-positioning in adjacent lanes (Yousif et al., 2017). It can, therefore, be inferred from this study that the higher the volume of HGVs in narrow lane situations, the more pronounced the adverse effects on traffic flow. Conversely, the adverse effects of narrow lanes is likely to be reduced where the number of HGVs is low.

6.3.2 Very high MPR

At very high MPR levels (e.g, 95% MPR), the solution with the lowest cost is for a standard CAT lane of 3.65m. A three-lane configuration is required here, with an MT and PC lane of 3.70m and 3.65m, respectively.

At this level of penetration, the cost savings from retaining the existing standard cross-section without incurring conversion costs and its attendant travel time disruption, is more than any CAT lane widening to take advantage of wander effects of connected autonomous vehicles, or the wider lanes of MT and PC lanes, if the CAT lane were to be narrower.

6.3.3 Evaluating highway design efficiency at varying MPRs

Comparing all three equations, the optimal cost occurs for a standard CAT lane of 3.65m at very high (95%) MPR.

The optimisation exercise and analysis of the resulting output showed that there are two optimal highway designs for introducing CAT depending on the MPR values. When MPR is very low to mid-range (5-50%) – a situation that is likely to prevail at the start of the introduction of CATs into the vehicle stream – the optimal highway design solution is 2.85m CAT lane within a four lane configuation, with a 3m MT lane and two 2.575m PC lanes. However, when MPR reaches the very high levels (95%), the optimal highway design solution occurs for a standard CAT lane of 3.65m. This corresponds to a three-lane configuration of standard lane width, with 3.70m for MT lane and 3.65m for PC lanes.

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Table 6-3 Regression analysis for cross-sections and MPR against whole-life costs

Regression Statistics	
Multiple R	0.9652
R Square	0.9317
Adjusted R Square	0.9313
Standard Error	66,287,652
Observations	550

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3.3E+19	1.1E+19	2483	0
Residual	545	2.4E+18	4.4E+15		
Total	549	3.5E+19			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	215,905,515	32,235.858	6.6977	0.0000	152,584,031	279,227,000	152,584,031	279,227,000
Lane 1: CAT Lane (m)	205,155,211	4,228,879	48.5129	0.0000	196,848,347	213,462,075	196,848,347	213,462,075
Lane 2: MT Lane (m)	194,320,389	8,622,794	22.5357	0.0000	177,382,478	211,258,300	177,382,478	211,258,300
MPR (%)	-5,866,251	93,511	-62.7330	0.0000	-6,049,937	-5,682,565	-6,049,937	-5,682,565

Table 6-4 Regression for MPR/whole-life costs – standard CAT Lane

Regression Statistics	
Multiple R	0.9902
R Square	0.9804
Adjusted R Square	0.86711
Standard Error	30,070,010
Observations	11

ANOVA

	df	***SS***	***MS***	***F***	***Significance F***
Regression	2	4.07526E+17	2.04E+17	450	0
Residual	9	8.13785E+15	9.04E+14		
Total	11	4.15664E+17			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1,541,847,306	17,525,046.35	87.97964	0.0000	1,502,202,897	1,581,491,715	1,502,202,897	1,581,491,715
MPR (%)	-6,367,877.706	299,951.1609	-21.2297	0.0000	-7,046,414	-5,689,341.039	-7046414.374	-5,689,341.039

Table 6-5 Regression for cross-section and MPR/whole-life costs – CAT lane ≤ 3.00m

Regression Statistics	
Multiple R	0.9905
R Square	0.9811
Adjusted R Square	0.9712
Standard Error	9,853,629
Observations	110

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	5.4E+17	1.3E+17	1839	0
Residual	106	1.0E+16	9.7E+13		
Total	110	5.5E+17			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	917,635,075	111,827,878.86	8.21	0.0000	695,925,429	1,139,344,721	695,925,429	1,139,344,721
Lane 1: CAT Lane (m)	77,332,515	21,696,976.50	3.56	0.0005	34,316,149	120,348,882	34,316,149	120,348,882
Lane 2: MT Lane (m)	28,185,987	21,696,976.50	1.30	0.1967	- 14,830,379	71,202,353	- 14,830,379	71,202,353
MPR (%)	- 2,305,691	31,082.30	- 74.18	-	- 2,367,315	- 2,244,067	- 2,367,315	- 2,244,067

Chapter 7 DEVELOPMENT OF DECISION MODEL TO SUPPORT OPTIMISED ROAD DESIGN IMPLEMENTATION

In this Chapter, the impact of vehicular traffic demand levels on performance metrics for road designs optimised for connected autonomous trucks is presented. It explores the role of traffic flows in assessing highway engineering alternatives and highlights the importance of understanding how traffic volumes affect the benefits of self-driving vehicles.

The chapter also critically analyses previous research on the relationship between traffic demand and connected autonomous vehicles (CAVs) and highlights the need for more comprehensive and statistically reliable studies. The approach to scenario generation and simulation is described, followed by an analysis of the net benefits for variable vehicle demand and penetrations.

The section concludes with a predictive model derived from regression analysis, which can be used as a decision-making tool to evaluate the impact of implementing connected autonomous truck-enabled highway designs on traffic performance metrics.

7.1 Impact of vehicular traffic demand levels on performance metrics for road designs optimised for connected autonomous truck

7.1.1 Establishing the role of traffic flows in assessment of highway engineering alternatives

When transportation problems are to be addressed, traffic volume is one of the main factors that determines the suitability of engineering proposals, as the efficiency of traffic interventions is highly sensitive to volume of traffic. Interchange or junction types, lane widths, and number of lanes are all design decisions based on traffic levels.

The use of Intelligent Transport Systems (ITS) and more broadly, technologies in transport, are also heavily influenced by traffic demands. For instance, the deployment of the Smart Motorways concept and choice of signal control systems, are, at least, partly determined by capacity requirements.

With the preceding chapter concluding that the optimal cross-section for typical UK motorway flows is a non-standard four-lane with very narrow CAT lane, it was necessary to investigate the impact of variable traffic volumes on this design solution. Therefore, it is important to test the validity and generalisability of the derived optimised cross-section for connected autonomous truck-enabled highway, against a range of traffic demand levels.

7.1.2 The case for optimal design solution validation against varying traffic flow impacts

The generally held view within the connected and autonomous vehicle (CAV) sector is that self-driving technology will improve the key measures of transportation performance, namely safety, greenhouse gas emissions, and traffic flows. However, this perspective is not totally undisputed. Particularly, on the point of traffic flow, specific studies have shown that this could worsen under CAVs (Michael et al., 1998).

As traffic volumes can vary widely from one motorway to the other, it is imperative to understand how this variation impacts on the benefits achieved from self-driving vehicles, so that the introduction of CAVs can be streamlined.

7.1.3 Exploring insufficiencies within previous studies on demand-CAV relationships: critical analysis of prior research

The HumanDrive Project in the UK carried out by Mesionis et al. (2020) showed that benefits from CAVs increased for congested traffic conditions, with benefits reducing in free flow situations, due to the elimination of merge/diverge and lane change manoeuvres. However, a core modelling premise within the methodology used by the HumanDrive research team assumed that trucks remain non-CAV. This is against the predictions based on comprehensive analysis that supports the forecast that trucks are the more likely vehicle category to adopt CAV technology within mainstream public road situations (Hummer, 2020).

In addition, the study was predicated on a driving regime based on shared carriageway operations, where manual and autonomous vehicles are allowed to mix. This is at variance with the well-supported segregated CAV lane configuration. Moreover – and crucially - only one base traffic volume was used, and although a 5% annual growth rate was applied to account for future growth, this still did no cover the range of AADT on motorways.

Other researchers, however, did examine traffic flow effects for using innovative cross-sections for autonomous vehicles in dedicated CAV lane operational regime. In particular, the National Cooperative Highway Research Program (NCHRP) investigated the benefits of various dedicated lane options, concluding that shared dedicated lanes were the most suitable option at lower MPRs and exclusive dedicated lanes at mediums MPRs; dedicated lanes were discouraged at high MPRs. The limitation of the NCHRP study was that the geometrical features of the dedicated lane was based on a standard High Occupancy Vehicle Lane.

In addition, although a range of traffic flow volumes were investigated, these were applied to different case study sites, with each having unique and different geometries. This statistical non-comparability of the sampling scenarios meant interpreting the effect of AADT values on performance could lead to unreliable results, as other factors could have affected the outcome (National Academies of Sciences and Medicine, 2019).

Additionally, a study of the motorway system in the Netherlands researched the impact of using different methods to separate the dedicated CAV lane - as well as the lane position within the carriageway - using driving simulator with test subjects. But this was based on Dutch national road design standards, so lane widths were limited to standards ones. Traffic volume effects were not included in this research, either (Schoenmakers et al., 2021).

Similar simulator-based research by Rad et al. (2021), also in the Netherlands, only investigated one type of penetration (43% MPR). The results from this study also have very limited application for analysing the effects of traffic volume variability for optimised highway design, in that there was no variation in traffic flow volumes, neither were non-standard cross-section explored.

So, while there have been various studies relating CAVs performance to levels of vehicular traffic demand, they are lacking in either the level of variability in the scenarios to allow significant statistical conclusions to be drawn from their results, and/or use standard lane widths, which are sub-optimal for accommodating connected autonomous trucks. Hence, there is a necessity for an evaluation that incorporates comprehensive scenario variability for more accurate statistical modelling.

7.1.4 Approach to scenarios generation and simulation

An effective way to developing a model that predicts the benefits of CAVs for various traffic flows, is to simulate and analyse multiple scenarios. The outputs generated are then statistically modelled.

As was done in Chapter 5, transportation, mathematical and economics models, which have been developed based on manual vehicles (MVs), were modified to account for the unique characteristics of autonomous driving behaviour. These modified models were used to calculate accidents, emissions, fuel consumption and travel time costs for dedicated CAT lane scenarios. However, unlike was done in the aforementioned design optimisation chapter, initial conversion was not required. This is because as the same optimal cross-section re-modelling solution was applied to all the cases.

For the analysis of the optimal highway design solution against traffic flow volumes, a further 275 scenarios were simulated. Eleven market penetration rates (MPRs) were used to represent very low to very high CAV uptakes. This resulted in MPRs of 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 95%, similar to the MPRs tested in the whole-life cost calculations in Chapter 5.

The approach used to select traffic volumes was on the basis that Pre-COVID, the most trafficked motorways in the UK, such as the M25, regularly recorded daily flows of 200,000 (Department for Transport, 2022). So, to increase the versatility of the results analysis this maximum recorded flow was adjusted upward by 25%; hence an upper AADT of 250,000 was included. The lowest traffic volume used was 5,000 AADT to represent the least congested conditions; below this demand level, traffic disruption caused by highway geometric amendments are not likely to be at detectable levels for this study. Also pavement failure from loading at sub-5,000 AADT is not significant, due to negligible million standard axle (msa) values (Highways England, 2020c).

The AADTs were then increased by 5,000 or 10,000 with an additional AADT of 83,300 to capture typical flows on UK motorways. In all twenty-five AADT values were generated.

For each scenario, a whole-life cost was calculated for a baseline, and then a CAT regime. As described previously in Section 5.2, the baseline regime used an existing conceptual standard three-lane motorway. The CAT regime was based on remodelling the baseline to the optimal design, i.e., a non-standard four-lane cross-section incorporating a 2.85m wide dedicated CAT lane and three narrow lanes for manual vehicles.

The net cost benefit was then calculated, this being the different between the whole-life costs for a baseline scenario and the corresponding optimised cross-section design scenario for the level of AADT and variable MPR. Negative benefits represented a deterioration in the highway performance for the related levels of daily vehicular flows and MPRs, compared to its current existing condition without autonomous vehicles and utilising standard cross-sections.

7.2 Results of net benefits for variable vehicle demand and penetrations

The results of the net benefits for various average daily vehicle flows and MPR values are shown in Figure 7-1. Under the dedicated CAT lane regime, it can be observed that, generally, there is net disbenefit in introducing small proportions of CATs (5-10%), except for very highly traffic roads (above 170,000 AADT). With part of the carriageway dedicated to CAT traffic, manual vehicles become squeezed into a reduced space. Hence there must be high CAT traffic (and by extension high overall traffic) before this exclusive CAT space becomes worth it.

Therefore, at low levels of penetration for low levels of traffic, it could be more beneficial to operate mixed CAT/manual vehicle lanes to maximise roadspace use. However, this research scope only investigated dedicated lane scenarios, and this potential benefit of mixed traffic operation has not been quantified

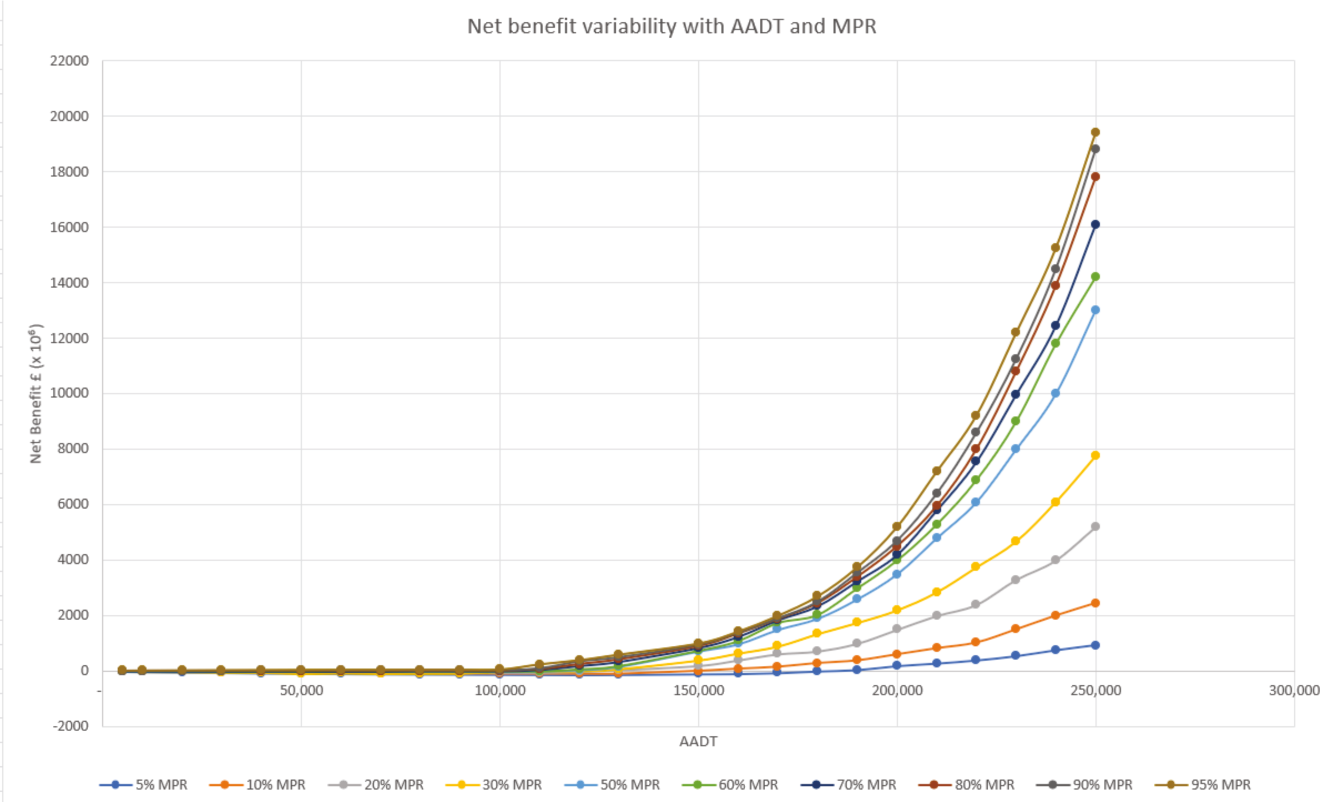

Figure 7-1 Net benefit variability with AADT and MPR

There is an additional interesting observation for very low MPRs: the net benefit function is concave shaped. Here, the worse performance occurs for high AADTs (100,000 to 120,000), with net cost of £125m per section (3km length) and £102m per section over 20 years for 5% and 10% MPR, respectively. The other ranges of AADTs (i.e., low, medium, and very high flows) perform better in this case. This is because, at these high flows, there is increased damage to the narrow CAT lane pavement from trucks, due to close tracking of CAT wheels. This leads to more frequent capital maintenance cost to repair the pavement, coupled with traffic disruption costs. And although the CAT offer some benefits in terms of safety and operational flows, this is not sufficient to overturn the costs.

As MPR increases, the gradient on the left-hand side of the AADT/net benefit curve reduces, and the benefit increase exponentially. So, for low MPRs (20-30%), benefit remains negative and nearly constant until approximately 120,000-130,000 AADT, and for medium MPR (50-60%), net benefit flatlines in the negative region until approximately 100,000-110,000 AADT. Then, from high (70-80%) to very high (90-95%) MPR, the costs and benefits effectively cancel each other out (£0 net benefit) until about 100,000 AADT. From these points onwards, there is an exponential increase in net benefit.

Significantly, there are net gains in benefits from 180,000 AADT even at very low MPRs, and these benefits increase in value with increasing MPR and AADT. Also, as MPR increases, the threshold AADT at which net positive benefit occurs reduces. As a comparison, in medium MPRs (50-60%) net benefit occurs at 120,000 AADT, while at very high MPR (90-95%), there is a net positive benefit even at low AADT of 5,000.

Although MPRs increase the net benefits, AADTs have a much more profound impact, as shown in the curves in Figure 7-1. The relatively smaller MPR impact is explained by how the traffic data used in this study simulations were generated, particularly with respect to the underlying assumptions that only trucks have connected autonomous vehicles functionalities, and that the total of the truck volumes constitutes 11% of the total AADT. With increasing AADT, more trucks are introduced, leading to growth in realising the benefits of autonomy.

7.3 Analysis of aggregated net-benefit variability

7.3.1 Predictive model derivation for net benefits

The data from the individual MPRs were aggregated, and then regression modelling used to estimate the relationship between MPR and AADT as two independent variables, and net benefit as the dependent variable.

The result of the regression modelling is shown in Table 7-1. The Multiple R value of 0.981 indicates a strong positive correlation between AADT (Average Annual Daily Traffic) and MPR (Market Penetration Rate) as independent variables, and the net benefit as the dependent variable. The R Squared value of 0.963 indicates that 96.3% of the variability in the dependent variable can be explained by the independent variables.

Furthermore, the table shows that the regression model is significant ($p < 0.05$), and the coefficients table indicates that both AADT and MPR are significant predictors of the dependent variable, as their p-values are also less than 0.05 (to four decimal places both are approximately zero).

Mathematically, the regression model from these results can be expressed as:

$$\text{Benefit} = 4.93 \times e^{(2.73 \times 10^{-5} \times AADT + 0.0166 \times MPR)} \qquad \text{Equation 7-1}$$

The model shows that benefit increases exponentially with AADT or MPR. The coefficients show that MPR causes a faster increase in benefit compared to traffic volume.

Table 7-1 Regression model result for AADT-MPR-Net Benefit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981
R Square	0.963
Adjusted R Square	0.957
Root Mean Square Error	726.02
Significance F	0.0000
Observations	275

Model Parameters

	Coefficients	**Standard Error**	**t Stat**	**P-value**
Constant	4.9311	0.75224	-6.5552	0.0000
AADT	2.7292×10^{-5}	6.2256×10^{-7}	43.8385	0.0000
MPR (%)	1.6612	5.0604×10^{-2}	32.8284	0.0000

7.3.2 Limitations of mathematical model

As discussed in Section 7.2 above, for lower values of AADT, there can be a disbenefit in introducing CATs, ie, negative benefit. However, as the model is an exponential equation with a positive baseline coefficient, all the benefits it produces will be positive. Hence, generally, the model is more accurate for AADT values at 180,000 and above.

Breaking down the model's behaviour further, the regression over-estimates the net benefit at low and high MPRs, while underestimating at mid-range MPR values. The difference increases with increasing AADT in these MPR ranges. This behaviour of the model in terms of its accuracy in predicting the net benefits at different MPR levels is illustrated in Figure 7-2.

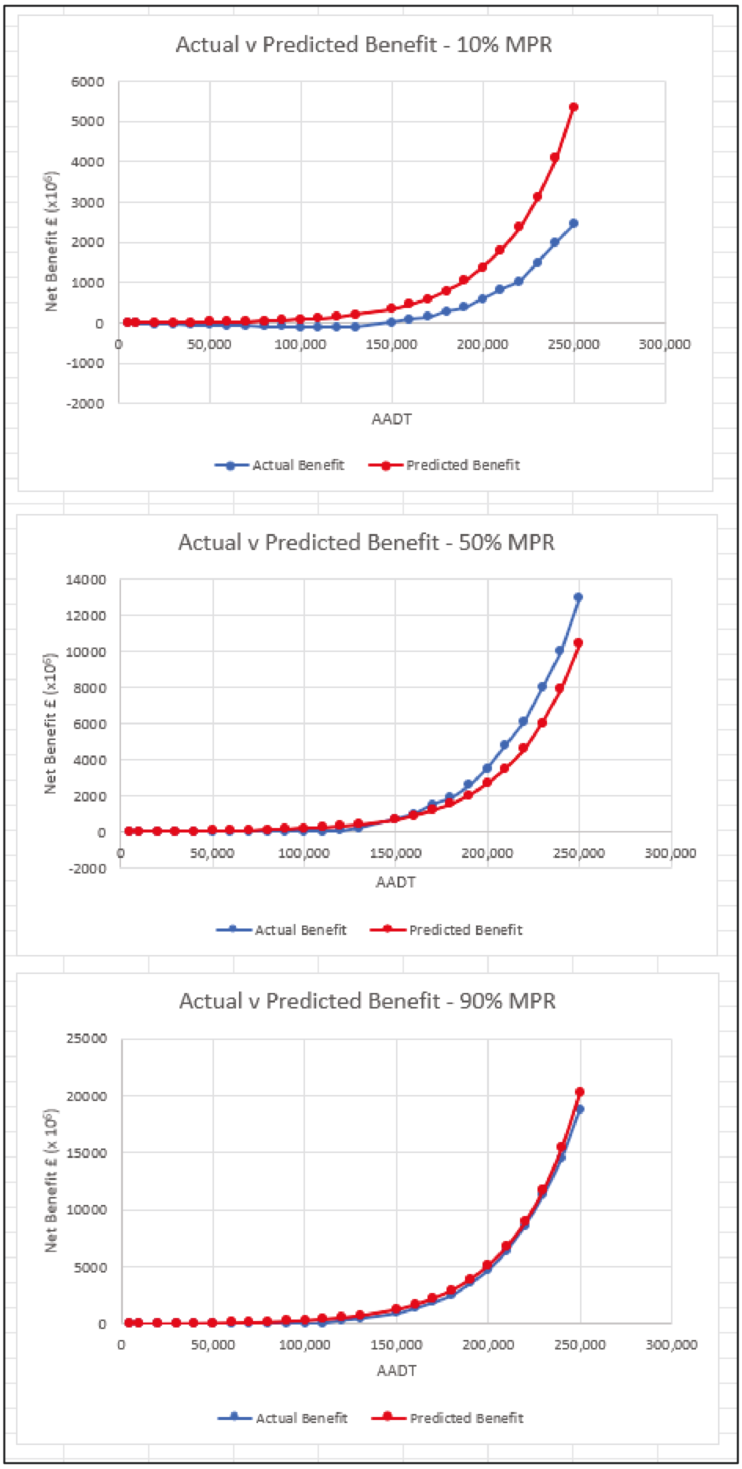

Figure 7-2 Model accuracy at various MPR levels

Chapter 8 SUMMARY AND CONCLUSION

8.1 General findings

8.1.1 Whole-life cost approach to highway design assessment for CATs

The research investigated, quantified, and compared key whole-life components for remodelling an existing conceptual standard motorway to implement a segregated lane for connected autonomous trucks. Different scenarios were formulated. Costs associated with initial conversion, pavement deterioration rates and maintenance frequency, safety, fuel consumption and energy, emissions, and travel time costs were analysed.

Subsequently the mathematical models of costs associated with the different options for constructing dedicated CAT lanes, as well as the costs of maintaining and operating these lanes are calculated.

Pavement, one of the most importation infrastructural components of the highway system, was analysed using a bespoke software programme, TxME. Industry standards and guidance documents on roadworks safety were used in modelling road layouts during construction and maintenance.

8.1.2 Variation of individual Cost components

The findings revealed that narrow CAT lanes incur the highest initial conversion cost due to the need to create three separate and additional lanes Generally, the more the CAT lane deviated from the standard 3.65m width, the higher the conversion cost. Standard CAT lane width of 3.65m did not incur any conversion cost as the existing highway is retained.

Regarding pavement maintenance frequency and costs, the study shows that a very wide CAT lane of 5m implemented at a high penetration rate of 95% produces the lowest maintenance cost. The highest maintenance cost occurs for mid-range MPR of 50% when both CAT and MT lanes have sub-standard 3m wide lanes.

The lowest accident cost occurs for the standard CAT lane width for all MPRs, while the highest accident cost occurs for 3m CAT lane width.

Furthermore, fuel consumption, energy expended, and emissions generated were found to also increase with increasing CAT lane width. When CAT lanes become wider, the manual vehicles are forced to use a narrower section of the carriageway, leading to high vehicle densities and a less stable flow.

Travel time costs generally increase with increasing CAT lane width, except for the standard lane width of 3.65m. The travel time cost generally decreases with increasing MPR due to CATs being more likely to travel closer to desired speeds, and increased platooning reducing the number of drivers required.

8.2 Optimal highway design solutions

The essence of developing an optimisation highway design model is to respond to a situation where autonomous vehicles are invariably being introduced, and the highway engineer has to produce the best design model.

Based on typical motorway AADT flows of 83,300 and 11% HGV content, there are two optimal highway designs for introducing CAT depending on the MPR values. The derivation of the solution is based on non-widening reconfiguration of an existing dual three-lane standard motorway cross-section of traffic lanes 3.65m, 3.70m and 3.65m, totalling 11m.

When MPR is very low to mid-range (5-50%) – a situation that is likely to prevail in the immediate to medium term for CATs introduction – the optimal highway design solution is a four-lane configuration consisting of a 2.85m CAT lane a 3m manual truck lane and two 2.575m PC lanes.

However, when MPR reaches the very high levels, the optimal highway design solution occurs for a standard CAT lane of 3.65m. This corresponds to a three-lane configuration of standard lane width, with 3.70m for MT lane and 3.65m for PC lanes.

Ultimately, between these two situations, it was found that the optimal highway design (lowest WLC) occurred for non-standard cross-section incorporating four narrow lanes: 2.85m CAT lane, 3m MT lane and two 2.575m wide PC lanes and this occurred at very high MPR levels. The high lane discipline expected from CAT will lead to more stable traffic flows, improving journey times for all vehicles. With the trucks unlikely to use the inner lanes, narrow lanes for PCs can be implemented, allowing an extra lane to be fitted.

But, as MPR is not within the control of designers, the appropriate solution would need to be assessed based on prevailing MPRs for the subject road network.

8.3 Impact of traffic volumes on net cost/benefits

Further work was undertaken to analyse when changes to highway would be required based on varying traffic volumes. The key results here were that:

- Overall, for any values of AADT, maximising MPR increases the benefits of the highway.
- For low MPR values, introducing CATs only has a positive benefit when traffic flows are high or extremely high (≥180,000 AADT).
- Conversely, introducing CATs at low MPR values when AADT is lower than 180,000 results in negative costs.
- Generally, for the highest values of MPR (at least 95%), net positive benefits begin to accrue when AADT is at least 21,000. Below this the cost is negative.

At the lower levels of traffic demand, the safety, traffic flow and fuel consumption benefits of CATs are not enough to balance out the traffic disruption of placing all the manual traffic into the remaining carriageway width, which has been reduced to create a dedicated CAT lane. At the start of the introduction of CATs, when this is going to be a gradually increasing introduction, this will worsen traffic performance for light to medium traffic roads. Only very highly trafficked roads would rip benefits.

Generally, benefits increase with increasing MPRs and AADT, due to the travel time, safety and emissions benefits from more CAT.

This study shows the impact of different AADT and MPR values from a cost/benefit perspective, and highlights the complexities of determining a solution that ensures the introduction of CATs is carefully considered.

8.4 Accomplishment of the research goals and contributions to knowledge advancement

The thesis methods were designed and followed to achieve the objectives set out in Chapter 1. In pursuing and achieving these objectives, some contributions to the advancement of knowledge in the field of highway design for connected autonomous vehicles were produced.

8.4.1 Objective 1: Conduct exploratory study into highway designs parameters that require modifications for CAVs

In Chapter 2, a thorough review was conducted investigating the operational behaviours of CAVs. Details were provided assessing how the technological characteristics of autonomous vehicles would imply that they function markedly differently from manual vehicles.

The underlying principles of highway engineering are explored in detail in Chapter 3, concluding that, because of the expected operational behaviour of autonomous vehicles, coupled with the current design principles being potentially unsuitable to CAVs, a method for optimising highway design for CAVs was necessary.

In particular, the lateral clearance requirements which govern cross-sectional widths were highlighted as a likely feature in need of redesigning for autonomous vehicles. The indeterminate lane choice models for manual trucks also meant that cumulated traffic wheel loading for the more predictable CAT traffic could impact on pavement failure profiles.

Resultantly, it was found that cross-sections and pavement designs had to be analysed for CAVs. Chapter 4 systematically reviewed existing research carried out in these two areas for autonomous vehicles.

In the end, the exploratory study determined that cross-section and pavement design features had to be studied further for autonomous vehicles. This had to be done together due to their mutual inter-dependencies.

8.4.2 Objective 2: Develop methodologies for calculating new highway performance metrics for CAVs

Within Chapter 5 and Chapter 6 of this thesis, existing mathematical traffic models and transport economic models which have been developed for manual vehicles were amended to produce new models for CAVs.

These newer models drew on secondary data obtained by accessing the current suite of research findings on the behaviour of CAVs, including wheel lateral control safety, fuel consumption, vehicle distributions and adherence to speed limits.

These new CAV models can be used in various traffic modelling applications; they present a simple and flexible way of modifying parameters and observing their impact, which is important for efficient working, as researchers' understanding of CAVs is constantly improving. The breakdown of costs can also be useful in determining the extent to which different metrics change with the different cross-section features and MPRs.

8.4.3 Objective 3: Produce whole-life cost optimisation model for highway design for CAVs

In Chapter 6, the approach used to develop a variety of different alternatives to generate whole-life cost values is outlined. These alternatives were obtained by modification of a conceptual base case standard cross-section.

Models for the different whole-life cost elements: initial conversion, safety, fuel consumption, emissions and travel time costs, were derived. These are expressed in terms of the various transport input variables. Applying a combination of different MPRs and cross-sections, 550 scenarios were generated. Multiple linear regression modelling was then used to derive three models relating the cross-section values and CAT proportions as input variables, to the calculated whole-life costs as the response variable. The three models apply to different lane width values for the CAT lane. Using these regression models, researchers will be able to compare the impacts of different highway design interventions and CAVs implementation/operational regimes.

Based on the lane constraints, and depending on MPR values, an optimised design solution was obtained, demonstrating how a motorway carrying typical UK traffic flow volumes could be re-configured for CAVs to optimise its whole-life cost performance.

8.4.4 Objective 4: Validate the performance of the optimised highway design model against a range of traffic flow conditions

Because the optimised model was derived using typical AADT values, the derived optimised cross-section was further analysed against different vehicular traffic flow volume conditions.

Similar to the method used to accomplish Object 3, regression modelling was used to derive a relationship between AADT and CAT proportion, with net benefits as the response parameter.

This produced a decision support model that can be used to predict the net benefit for implementing the optimised model, depending on the traffic flow conditions. The model shows that, although CAVs are generally expected to provide improvements for the highways due to their operational benefits like safety and fuel consumption, there are also disbenefits associated with the disruptive effects of their implementation. This decision support model can help determine where that balance lies between positive and negative impacts of CAVs.

8.5 Practical applications of the research

It is envisaged that the main application of this research will be the ability to implement cross-sections designs optimisation, as well as pavement re-analysis to account for the driving and movements of CATs. These are explored in the following sections

8.5.1 Cross-sections optimal designs and pavement re-analysis

This study examined the technical feasibility and challenges of alternative cross-section under normal operations and temporary situations. The findings can be used to remodel highways for CAVs. The results can support Departure from Standards applications to National Highways for using innovative solutions to accommodate CATs.

Current DMRB design standards for pavements and geometry do not account for CAVs. The results from this research can then be correlated with UK DMRB pavement designs, and equivalent pavement damage wear factors deduced for the different CAT wheel wander regimes. A longer-term study should then seek to correlate and validate in-operation pavement performance under CAT loading, once CAVs start to become mainstream.

8.5.2 Application of model as a decision tool for autonomous vehicles implementation

As a result of the Benefit-AADT-MPR model derived herein, a quantifiable value can be obtained for the net benefit from implementing a CAT-enabled highway system. For road authorities and policy makers, traffic demands are usually not within their control. However, using existing and/or forecast traffic flows, road operators would be able to calculate what levels of penetration of autonomous vehicles will lead to a net positive impact.

Another area that this model could be used is in the ranking of CAT projects. So, for different vehicular traffic flow volumes, benefits for different projects can be determined using the decision model. And if funding needs to be prioritised, the model can be applied as an object measure of the expected outcomes. By this, Value for Money for highway projects with autonomous vehicles can be achieved.

In summary, the findings of this study provide valuable insights into the costs and benefits associated with different CAT lane options. The results can inform policymakers and transportation planners in making decisions on the optimal CAT lane width to implement, based on factors such as initial conversion cost, maintenance cost, safety, fuel consumption, emissions, energy costs, and travel time costs.

8.6 Areas requiring further research

Despite introducing some significant viewpoints on the introduction of connected autonomous vehicles, presenting important revelations in deriving a method for optimising highway designs, and providing an informative decision support model for introducing connected autonomous truck lanes, there are a number of ways this research could be extended.

8.6.1 Expansion of the geometric design alternatives investigated

Firstly, this study will benefit by expanding the cross-section scenario alternatives to include a dedicated offside CAT lane. Such a configuration could introduce very different vehicle flow dynamics into the modelling, which is likely to affect the results of the whole-life costs components, and hence, the multiple linear regression model on which the cross-section optimisation was based. The location of the CAT lane (offside or nearside) could then be included in the modelling and optimisation as a binary, discrete decision variable that affects whole-life cost.

Additionally, the current study was completed using a conceptual 3km highway link section to eliminate the impact of complex maneouvres at junctions. A roll-out of the research to include an entire network that encompasses the complexities of road systems will present a ‘bigger picture’ perspective on the problem of introducing connected autonomous vehicles.

Furthermore, diversifying the cross-section alternatives by including carriageway widening options would further enhance the range of researched scenarios. Although initial studies showed that road widening incurred disproportionate cost, and hence did not feature in the scenarios used in the optimisation, these initial studies used full lane width widening. More modest widening options could be investigated and including to understand their impact on the highway design optimisation.

Another aspect of the research that could gain from more work is the development of the decision support tool that relates net benefits to vehicular traffic flow volumes. The derived model is based on the optimised highway cross-section, which was obtained by simulations using typical motorway flow conditions. It may be that different daily vehicular flow volumes will result in different optimised cross-section designs, and this would affect the model. Extending this research in this way could culminate in an interesting new model relating AADT and MPR to an optimal highway cross-section that ensures a net positive benefit for introducing connected autonomous vehicles.

8.6.2 Modifying and using the pavement structural attributes as predictor variable

This research used a typical, standard pavement structure to carry out the analysis. This meant that opportunities to introduce pavement construction depth into the regression modelling as one of the regressor variables was absent. The differential response to AV wander loading exhibited by different flexible pavement layer thicknesses has been established (Yeganeh et al., 2023).

Also, different pavement structural forms have not been investigated, with the analysis based on a multi-layered asphaltic concrete flexible system exhibiting viscoelastic properties under traffic wheel loadings. The effects of using rigid pavements such as ground-bearing reinforced concrete slabs have not been included. Whereas the loads imposed by the various wheel wander regimes of CAT on flexible pavements use soil theories, analytical models for concrete pavements are based on plate theory, which assumes that loads are distributed by beam action. In analysing rigid systems, the theory of elastic foundations is applied to the underlying supporting layer, which is modelled as a dense, viscous medium acting as a series of springs to support the slab. The general structural failure mechanism is when the wheel loads generate horizontal tensile stresses on the underside of the slab until a tensile crack is initiated.

Composite pavements, which combine flexible and rigid systems, are also widely used in the construction of highway projects, and could be included in the analysis to expand the scenarios even further.

The differences in the underlying theories for different pavement types could yield different failure frequencies under the same loadings, and this could affect the optimisation modelling.

8.6.3 Basis and assumption for composition of traffic data used in analysis

Some very important assumptions are used throughout the study in the generation of traffic data for the simulations. These include:

- HGV volumes are as per the typical proportion on UK motorways, i.e., 11% of the total traffic flow volume.
- Non-HGVs remain as manual vehicles over the design period of 20-years
- Uptake in CAT does not impact the forecast traffic growth rate

However, as demonstrated within the whole-life costing, travel time and delay costs are heavily influenced by PCs. So, where the HGV content is very different from the average 11%, the outcome of the cross-section optimisation, as well as the net benefit decision tool conclusions, may produce very different models. In effect, HGV content could be introduced into the data analysis as an additional input parament to test its effects on the results.

Again, allowing for some of the PCs to be connected autonomous vehicles will affect the modelling. Further analysis to account for this could include either combining both CAV trucks and PCs in one dedicated lane or have two separate lanes for CAV trucks and truck PCs.

Different traffic growth forecasting models could also change the benefits from CATs, and this could be investigated in further studies.

8.6.4 Exploring potential scope for research broadening

The focus of the research is on civil engineering infrastructure. However, technological infrastructure required to support connected autonomous driving may impact significantly on road infrastructure. The cost of these technological systems could be included in future studies on whole-life cost determination. Related to this, the assumptions made for the vehicle operational cost models for CAVs could be refined in the future, requiring a different approach to whole-life cost calculations.

Moreover, the current research is based on a 3km highway link. Effects of weaving and merge/diverge maneouvres at junctions have not been studied. Junctions introduce complex vehicle flow dynamics and installing a dedicated lane through junctions would need to be studied further and added to the analysis.

Finally, the study has used several mathematical transportation models to simulate transport outcomes. This afforded the flexibility of being able to manipulate parameters and easily observe their impacts. Although the original forms of these models were devised and validated for manual vehicles, they were modified for connected autonomous vehicles for the purposes of this research. As real-world data for CAVs are not yet widely available and accessible, a validation exercise could be undertaken for both the optimised model and the decision support model, using dynamic transportation simulation software that contains in-built parameters for autonomous driving. This would increase confidence in the results and models derived from the research.

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Appendix A DETAILED SCENARIO COST DATA – TYPICAL FLOWS

Appendix A

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)																							
						Maintenance over design life			isruption time: Construction roadwork			sruption time: Maintenance roadwo			Travel time during normal operations				Fuel Consumption				CO2 Emissions				
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	WLC - Dual carriagway per km
2.850	3.000	2.575	2.575	5	152,254	317,925	4,530,750	4,848,674	26,937,359	43,900,155	43,900,155	93,070	4,801,361	15,250,885	814,984	87,254,373	228,026,758	34,648,037	25,733,136	6,755,806	4,151,725	36,640,667	68,822,623	16,652,454	1,063,185	86,538,262	409,204,664
2.850	3.050	2.550	2.550	5	152,254	317,925	4,606,262	4,924,187	26,937,359	43,900,155	43,900,155	93,747	4,836,287	15,361,823	814,509	86,550,345	228,947,157	34,686,615	25,711,483	6,772,674	4,151,725	36,635,882	68,764,713	16,694,031	1,063,185	86,521,929	409,508,269
2.850	3.100	2.525	2.525	5	152,254	317,925	4,347,362	4,665,287	26,937,359	43,900,155	43,900,155	91,402	4,715,319	14,977,585	816,153	86,080,255	230,474,428	34,735,231	25,691,894	6,790,314	4,151,725	36,633,934	68,712,323	16,737,514	1,063,185	86,513,021	409,728,360
2.850	3.150	2.500	2.500	5	152,254	317,925	4,417,481	4,735,406	26,937,359	43,900,155	43,900,155	92,044	4,748,426	15,082,744	815,704	85,397,872	231,421,846	34,794,956	25,674,368	6,808,731	4,151,725	36,634,824	68,665,450	16,782,909	1,063,185	86,511,543	410,083,525
2.900	3.000	2.550	2.550	5	152,254	319,868	4,530,750	4,850,617	26,937,359	43,900,155	43,900,155	93,088	4,802,263	15,253,751	814,972	87,253,060	229,614,970	34,968,914	25,751,763	6,779,459	4,151,725	36,682,946	68,872,439	16,710,755	1,063,185	86,646,379	410,580,589
2.900	3.050	2.525	2.525	5	152,254	319,868	4,606,262	4,926,130	26,937,359	43,900,155	43,900,155	93,765	4,837,181	15,364,665	814,497	86,549,052	230,549,243	35,006,078	25,731,378	6,796,994	4,151,725	36,680,097	68,817,921	16,753,978	1,063,185	86,635,084	410,897,143
2.900	3.100	2.500	2.500	5	152,254	319,868	4,347,362	4,667,230	26,937,359	43,900,155	43,900,155	91,420	4,716,240	14,980,510	816,141	86,078,935	232,094,665	35,052,922	25,713,066	6,815,305	4,151,725	36,680,096	68,768,946	16,799,114	1,063,185	86,631,245	411,132,885
2.950	3.000	2.525	2.525	5	152,254	321,767	4,530,750	4,852,517	26,937,359	43,900,155	43,900,155	93,105	4,803,145	15,256,552	814,960	87,251,777	231,225,589	35,288,377	25,771,657	6,803,779	4,151,725	36,727,161	68,925,647	16,770,703	1,063,185	86,759,534	411,975,093
2.950	3.050	2.500	2.500	5	152,254	321,767	4,606,262	4,928,029	26,937,359	43,900,155	43,900,155	93,782	4,838,056	15,367,443	814,485	86,547,789	232,174,036	35,323,768	25,752,550	6,821,985	4,151,725	36,726,260	68,874,545	16,815,579	1,063,185	86,753,308	412,304,586
3.000	3.000	2.500	2.500	5	152,254	323,625	4,530,750	4,854,375	26,937,359	43,900,155	43,900,155	93,122	4,804,007	15,259,291	814,948	87,250,522	232,859,086	35,606,067	25,792,829	6,828,770	4,151,725	36,773,324	68,982,271	16,832,303	1,063,185	86,877,759	413,388,282
3.050	4.300	3.650	0.000	5	101,503	323,683	3,376,919	3,700,602	22,272,462	36,297,712	36,297,712	81,992	4,229,869	13,435,616	822,751	158,731,848	401,251,181	26,320,750	31,000,985	7,877,034	4,370,237	43,248,256	82,911,351	19,416,180	1,119,142	103,446,673	566,825,952
3.100	4.250	3.650	0.000	5	101,503	323,740	3,337,652	3,661,392	22,272,462	36,297,712	36,297,712	81,584	4,208,790	13,368,662	823,038	159,795,288	402,149,081	25,599,830	31,071,992	7,890,794	4,370,237	43,333,022	83,101,258	19,450,096	1,119,142	103,670,495	567,773,712
3.150	4.200	3.650	0.000	5	101,503	323,794	3,298,386	3,622,180	22,272,462	36,297,712	36,297,712	81,173	4,187,589	13,301,322	823,326	160,872,640	403,051,185	24,955,142	31,143,749	7,904,639	4,370,237	43,418,624	83,293,170	19,484,223	1,119,142	103,896,535	568,786,070
3.200	4.150	3.650	0.000	5	101,503	322,187	3,259,119	3,581,306	22,272,462	36,297,712	36,297,712	80,742	4,165,360	13,230,714	823,628	161,966,599	403,963,569	24,384,306	31,216,269	7,918,571	4,370,237	43,505,076	83,487,122	19,518,565	1,119,142	104,124,829	569,863,678
3.250	4.100	3.650	0.000	5	101,503	320,643	3,219,853	3,540,496	22,272,462	36,297,712	36,297,712	80,309	4,143,031	13,159,789	823,932	163,074,987	404,880,085	23,884,941	31,289,564	7,932,591	4,370,237	43,592,391	83,683,148	19,553,123	1,119,142	104,355,413	571,003,176
3.300	4.050	3.650	0.000	5	101,503	317,597	3,313,111	3,630,707	22,272,462	36,297,712	36,297,712	81,262	4,192,210	13,315,999	823,263	164,004,207	405,321,601	23,454,666	31,363,647	7,946,700	4,370,237	43,680,583	83,881,282	19,587,900	1,119,142	104,588,324	572,041,474
3.350	4.000	3.650	0.000	5	101,503	314,696	3,414,478	3,729,174	22,272,462	36,297,712	36,297,712	82,289	4,245,154	13,484,168	822,544	164,935,352	405,739,557	23,091,101	31,438,532	7,960,899	4,370,237	43,769,667	84,081,559	19,622,899	1,119,142	104,823,600	573,127,996
3.400	3.950	3.650	0.000	5	101,503	310,479	3,371,797	3,682,276	22,272,462	36,297,712	36,297,712	81,802	4,220,032	13,404,371	822,885	166,092,947	406,683,483	22,791,865	31,514,232	7,975,188	4,370,237	43,859,657	84,284,017	19,658,122	1,119,142	105,061,281	574,446,658
3.450	3.900	3.650	0.000	5	101,503	306,492	3,329,116	3,635,608	22,272,462	36,297,712	36,297,712	81,314	4,194,863	13,324,425	823,227	167,266,054	407,631,336	22,554,577	31,590,761	7,989,570	4,370,237	43,950,568	84,488,693	19,693,571	1,119,142	105,301,406	575,821,844
3.500	3.850	3.650	0.000	5	101,503	302,715	3,435,818	3,738,534	22,272,462	36,297,712	36,297,712	82,385	4,250,148	13,500,031	822,476	168,231,194	408,040,341	22,376,856	31,668,134	8,004,045	4,370,237	44,042,416	84,695,626	19,729,250	1,119,142	105,544,017	577,065,191
3.550	3.800	3.650	0.000	5	101,503	299,133	3,391,197	3,690,331	22,272,462	36,297,712	36,297,712	81,886	4,224,358	13,418,114	822,826	169,436,237	408,998,638	22,256,322	31,746,366	8,018,614	4,370,237	44,135,216	84,904,854	19,765,161	1,119,142	105,789,157	578,548,315
3.600	3.750	3.650	0.000	5	101,503	293,277	3,505,937	3,799,214	22,272,462	36,297,712	36,297,712	83,010	4,282,363	13,602,359	822,038	170,421,513	409,393,440	22,190,594	31,825,471	8,033,278	4,370,237	44,228,986	85,116,420	19,801,307	1,119,142	106,036,869	579,886,516
3.650	3.700	3.650	0.000	5	-	288,957	3,823,317	4,112,274	-	-	-	86,151	4,444,384	14,116,997	819,836	171,125,154	409,084,348	22,177,291	31,905,466	8,048,039	4,370,237	44,323,742	85,330,364	19,837,691	1,119,142	106,287,197	517,718,249
3.700	3.650	3.650	0.000	5	50,751	283,762	4,215,374	4,499,136	16,091,078	26,223,834	26,223,834	89,861	4,635,800	14,725,003	817,234	171,754,505	408,574,329	22,214,032	31,986,366	8,062,897	4,370,237	44,419,500	85,546,730	19,874,316	1,119,142	106,540,188	564,572,723
3.750	3.650	3.600	0.000	5	50,751	278,881	4,215,374	4,494,255	16,091,078	26,223,834	26,223,834	89,815	4,633,441	14,717,510	817,266	171,761,244	412,748,593	22,281,593	31,985,311	8,077,195	4,370,237	44,432,743	85,543,907	19,909,559	1,119,142	106,572,608	567,425,710
3.800	3.650	3.550	0.000	5	101,503	273,283	4,215,374	4,488,657	22,272,462	36,297,712	36,297,712	89,763	4,630,733	14,708,909	817,303	171,768,978	417,011,111	22,385,399	31,986,326	8,092,615	4,370,237	44,449,178	85,546,622	19,947,568	1,119,142	106,613,332	587,955,168
3.850	3.650	3.500	0.000	5	101,503	268,043	4,215,374	4,483,416	22,272,462	36,297,712	36,297,712	89,714	4,628,197	14,700,852	817,338	171,776,223	421,360,992	22,523,546	31,989,425	8,109,162	4,370,237	44,468,824	85,554,911	19,988,354	1,119,142	106,662,407	590,987,265
3.900	3.650	3.450	0.000	5	101,503	263,126	4,215,374	4,478,500	22,272,462	36,297,712	36,297,712	89,667	4,625,816	14,693,289	817,370	171,783,025	425,801,098	22,694,127	31,994,623	8,126,840	4,370,237	44,491,700	85,568,811	20,031,930	1,119,142	106,719,883	594,109,242
3.950	3.650	3.400	0.000	5	101,503	257,646	4,215,374	4,473,019	22,272,462	36,297,712	36,297,712	89,616	4,623,160	14,684,854	817,406	171,790,611	430,337,379	22,895,237	32,001,933	8,145,656	4,370,237	44,517,826	85,588,363	20,078,308	1,119,142	106,785,813	597,322,873
4.000	3.650	3.350	0.000	5	101,503	252,518	4,215,374	4,467,891	22,272,462	36,297,712	36,297,712	89,568	4,620,673	14,676,956	817,440	171,797,713	434,969,718	23,124,971	32,011,373	8,165,613	4,370,237	44,547,223	85,613,610	20,127,502	1,119,142	106,860,254	600,627,864
4.050	3.650	3.300	0.000	5	101,503	246,940	4,215,374	4,462,314	22,272,462	36,297,712	36,297,712	89,515	4,617,967	14,668,359	817,477	171,805,443	439,704,082	23,381,423	32,022,960	8,186,719	4,370,237	44,579,915	85,644,598	20,179,525	1,119,142	106,943,265	604,026,100
4.100	3.650	3.250	0.000	5	101,503	241,731	4,215,374	4,457,105	22,272,462	36,297,712	36,297,712	89,466	4,615,438	14,660,326	817,511	171,812,668	444,540,892	23,662,686	32,036,710	8,208,979	4,370,237	44,615,926	85,681,373	20,234,394	1,119,142	107,034,909	607,517,544
4.150	3.650	3.200	0.000	5	101,503	236,168	4,215,374	4,451,542	22,272,462	36,297,712	36,297,712	89,414	4,612,736	14,651,742	817,548	171,820,387	449,486,172	23,966,856	32,052,644	8,232,400	4,370,237	44,655,281	85,723,989	20,292,124	1,119,142	107,135,255	611,104,213
4.200	3.650	3.150	0.000	5	101,503	231,628	4,215,374	4,447,002	22,272,462	36,297,712	36,297,712	89,371	4,610,529	14,644,732	817,578	171,826,691	454,538,512	24,292,027	32,070,783	8,256,988	4,370,237	44,698,008	85,772,499	20,352,733	1,119,142	107,244,374	614,785,474
4.250	3.650	3.100	0.000	5	101,503	226,128	4,215,374	4,441,502	22,272,462	36,297,712	36,297,712	89,319	4,607,853	14,636,235	817,614	171,834,332	459,708,919	24,636,293	32,091,147	8,282,752	4,370,237	44,744,136	85,826,962	20,416,239	1,119,142	107,362,342	618,565,289
4.300	3.650	3.050	0.000	5	101,503	221,583	4,215,374	4,436,956	22,272,462	36,297,712	36,297,712	89,276	4,605,641	14,629,207	817,644	171,840,652	464,994,252	24,997,749	32,113,760	8,309,699	4,370,237	44,793,696	85,887,440	20,482,661	1,119,142	107,489,243	622,442,470
4.350	3.650	3.000	0.000	5	101,503	216,763	4,215,374	4,432,137	22,272,462	36,297,712	36,297,712	89,231	4,603,294	14,621,753	817,676	171,847,356	470,403,182	25,374,488	32,138,647	8,337,838	4,370,237	44,846,722	85,954,001	20,552,021	1,119,142	107,625,163	626,420,260
4.400	3.650	2.950	0.000	5	101,503	211,731	4,215,374	4,427,105	22,272,462	36,297,712	36,297,712	89,183	4,600,842	14,613,965	817,709	171,854,359	475,939,821	25,764,606	32,165,835	8,367,178	4,370,237	44,903,250	86,026,714	20,624,341	1,119,142	107,770,197	630,500,284
4.450	3.650	2.900	0.000	5	101,503	207,033	4,215,374	4,422,407	22,272,462	36,297,712	36,297,712	89,139	4,598,552	14,606,689	817,740	171,860,902	481,606,586	26,166,196	32,195,352	8,397,729	4,370,237	44,963,318	86,105,657	20,699,645	1,119,142	107,924,444	634,683,574
4.500	3.650	2.850	0.000	5	101,503	202,637	4,215,374	4,418,011	22,272,462	36,297,712	36,297,712	89,097	4,596,407	14,599,877	817,770	171,867,027	487,408,290	26,577,354	32,227,229	8,429,500	4,370,237	45,026,966	86,190,911	20,777,959	1,119,142	108,088,012	638,972,133
4.550	3.650	2.800	0.000	5	101,503	198,074	4,215,374	4,413,448	22,272,462	36,297,712	36,297,712	89,054	4,594,180	14,592,803	817,800	171,873,389	493,351,727	26,996,172	32,261,499	8,462,504	4,370,237	45,094,239	86,282,564	20,859,311	1,119,142	108,261,016	643,368,812
4.600	3.650	2.750	0.000	5	101,503	193,805	4,215,374	4,409,178	22,272,462	36,297,712	36,297,712	89,014	4,592,095	14,586,181	817,828	171,879,344	499,440,265	27,420,747	32,298,196	8,496,752	4,370,237	45,165,185	86,380,711	20,943,729	1,119,142	108,443,582	647,875,205
4.650	3.650	2.700	0.000	5	101,503	189,802	4,215,374	4,405,176	22,272,462	36,297,712	36,297,712	88,976	4,590,140	14,579,969	817,855	171,884,930	505,679,437	27,849,171	32,337,360	8,532,258	4,370,237	45,239,854	86,485,452	21,031,247	1,119,142	108,635,841	652,493,825
4.700	3.650	2.650	0.000	5	101,503	185,667	4,215,374	4,401,040	22,272,462	36,297,712	36,297,712	88,937	4,588,118	14,573,549	817,882	171,890,704	512,076,601	28,279,540	32,379,030	8,569,035	4,370,237	45,318,301	86,596,898	21,121,899	1,119,142	108,837,939	657,228,001
4.750	3.650	2.600	0.000	5	101,503	181,789	4,215,374	4,397,163	22,272,462	36,297,712	36,297,712	88,900	4,586,222	14,567,526	817,908	171,896,120	518,636,171	28,709,948	32,423,251	8,607,098	4,370,237	45,400,586	86,715,168	21,215,722	1,119,142	109,050,031	662,079,976
4.800	3.650	2.550	0.000	5	101,503	177,811	4,215,374	4,393,184	22,272,462	36,297,712	36,297,712	88,862	4,584,275	14,561,342	817,935	171,901,681	525,365,987	29,138,489	32,470,072	8,646,464	4,370,237	45,486,773	86,840,387	21,312,756	1,119,142	109,272,285	667,053,468
4.850	3.650	2.500	0.000	5	101,503	174,398	4,215,374	4,389,772	22,272,462	36,297,712	36,297,712	88,830	4,582,605	14,556,036	817,957	171,906,452	532,269,854	29,563,257	32,519,543	8,687,151	4,370,237	45,576,930	86,972,696	21,413,045	1,119,142	109,504,883	672,150,644
4.900	3.600	2.500	0.000	5	101,503	170,573	4,711,980	4,882,552	22,272,462	36,297,712	36,297,712	93,375	4,817,065	15,300,769	814,771	172,421,761	531,533,345	29,647,662	32,601,365	8,702,108	4,370,237	45,673,710	87,191,528	21,449,914	1,119,142	109,760,584	673,276,654
4.950	3.550	2.500	0.000	5	101,503	166,984	4,978,431	5,145,415	22,272,462	36,297,712	36,297,712	95,700	4,937,002	15,681,731	813,141	173,275,937	531,811,110	29,777,350	32,684,126	8,717,166	4,370,237	45,771,529	87,412,871	21,487,030	1,119,142	110,019,042	674,864,897
5.000	3.500	2.500	0.000	5	101,503	163,610	4,908,312	5,071,922	22,272,462	36,297,712	36,297,712	95,056	4,903,804	15,576,282	813,592	174,588,727	533,454,942	29,949,939	32,767,844	8,732,326	4,370,237	45,870,406	87,636,771	21,524,397	1,119,142	110,280,310	677,049,579
2.850	3.000	2.575	2.575	10	152,254	570,967	4,530,750	5,101,716	26,937,359	43,900,155	43,900,155	190,635	4,658,488	15,619,129	1,626,817	80,167,733	225,556,765	34,523,976	25,460,990	6,730,207	4,151,725	36,342,922	68,094,776	16,589,355	1,063,185	85,747,316	402,950,281
2.850	3.050	2.550	2.550	10	152,254	570,967	4,606,262	5,177,229	26,937,359	43,900,155	43,900,155	191,953	4,690,701	15,727,132	1,625,893	79,522,023	226,445,798	34,567,498	25,442,962	6,747,295	4,151,725	36,341,982	68,046,559	16,631,475	1,063,185	85,741,219	403,280,900
2.850	3.100	2.525	2.525	10	152,254	570,967	4,347,362	4,918,329	26,937,359	43,900,155	43,900,155	187,390	4,579,188	15,353,249	1,629,092	79,086,111	227,919,841	34,620,857	25,426,975	6,765,161	4,151,725	36,343,861	68,003,802	16,675,513	1,063,185	85,742,500	403,513,561
2.850	3.150	2.500	2.500	10	152,254	570,967	4,417,481	4,988,448	26,937,359	43,900,155	43,900,155	188,638	4,609,691	15,455,521	1,628,217	78,460,278	228,834,623	34,685,099	25,413,029	6,783,808	4,151,725	36,348,562	67,966,506	16,721,475	1,063,185	85,751,165	403,893,444
2.900	3.000	2.550	2.550	10	152,254	580,984	4,530,750	5,111,733	26,937,359	43,900,155	43,900,155	190,810	4,662,776	15,633,504	1,626,694	80,161,670	227,099,882	34,844,853	25,479,617	6,753,859	4,151,725	36,385,201	68,144,592	16,647,656	1,063,185	85,855,432	404,308,320
2.900	3.050	2.525	2.525	10	152,254	580,984	4,606,262	5,187,246	26,937,359	43,900,155	43,900,155	192,127	4,694,955	15,741,396	1,625,770	79,516,053	228,002,238	34,886,960	25,462,856	6,771,615	4,151,725	36,386,197	68,099,767	16,691,422	1,063,185	85,854,374	404,651,493
2.900	3.100	2.500	2.500	10	152,254	580,984	4,347,362	4,928,346	26,937,359	43,900,155	43,900,155	187,569	4,583,560	15,367,907	1,628,967	79,080,022	229,493,201	34,938,547	25,448,147	6,790,152	4,151,725	36,390,024	68,060,426	16,737,114	1,063,185	85,860,724	404,899,192
2.950	3.000	2.525	2.525	10	152,254	591,001	4,530,750	5,121,750	26,937,359	43,900,155	43,900,155	190,986	4,667,059	15,647,865	1,626,571	80,155,614	228,664,514	35,164,316	25,499,512	6,778,180	4,151,725	36,429,416	68,197,800	16,707,603	1,063,185	85,968,588	405,684,402
2.950	3.050	2.500	2.500	10	152,254	591,001	4,606,262	5,197,263	26,937,359	43,900,155	43,900,155	192,301	4,699,205	15,755,645	1,625,649	79,510,088	229,580,478	35,204,651	25,484,028	6,796,606	4,151,725	36,432,360	68,156,390	16,753,023	1,063,185	85,972,598	406,040,107
3.000	3.000	2.500	2.500	10	152,254	594,947	4,530,750	5,125,696	26,937,359	43,900,155	43,900,155	191,055	4,668,745	15,653,518	1,626,523	80,153,230	230,261,646	35,482,006	25,520,683	6,803,171	4,151,725	36,475,579	68,254,423	16,769,204	1,063,185	86,086,812	407,076,489
3.050	4.300	3.650	0.000	10	101,503	598,814	3,376,919	3,975,733	22,272,462	36,297,712	36,297,712	169,594	4,144,315	13,895,191	1,641,570	143,134,704	394,621,204	26,195,026	30,186,556	7,774,889	4,370,237	42,331,681	80,733,181	19,164,401	1,119,142	101,016,724	550,730,087
3.100	4.250	3.650	0.000	10	101,503	602,605	3,337,652	3,940,257	22,272,462	36,297,712	36,297,712	168,883	4,126,930	13,836,902	1,642,069	144,087,263	395,511,570	25,481,678	30,252,934	7,788,655	4,370,237	42,411,826	80,910,710	19,198,333	1,119,142	101,228,184	551,603,299
3.150	4.200	3.650	0.000	10	101,503	600,434	3,298,386	3,898,820	22,272,462	36,297,712	36,297,712	168,047	4,106,518	13,768,465	1,642,654	145,059,663	396,426,377	24,843,762	30,320,017	7,802,508	4,370,237	42,492,762	81,090,121	19,232,480	1,119,142	101,441,743	552,545,466
3.200	4.150	3.650	0.000	10	101,503	598,347	3,259,119	3,857,466	22,272,462	36,297,712	36,297,712	167,209	4,086,032	13,699,778	1,643,242	146,044,760	397,345,286	24,278,921	30,387,816	7,816,450	4,370,237	42,574,502	81,271,446	19,266,845	1,119,142	101,657,433	553,549,345
3.250	4.100	3.650	0.000	10	101,503	590,815	3,219,853	3,810,668	22,272,462	36,297,712	36,297,712	166,254	4,062,708	13,621,577	1,643,911	147,049,893	398,287,530	23,784,801	30,456,341	7,830,481	4,370,237	42,657,058	81,454,716	19,301,430	1,119,142	101,875,287	554,619,384
3.300	4.050	3.650	0.000	10	101,503	588,997	3,180,586	3,769,584	22,272,462	36,297,712	36,297,712	165,411	4,042,106	13,552,501	1,644,502	148,061,091	399,214,523	23,359,046	30,525,605	7,844,602	4,370,237	42,740,444	81,639,961	19,336,237	1,119,142	102,095,340	555,742,624
3.350	4.000	3.650	0.000	10	101,503	576,942	3,141,320	3,718,262	22,272,462	36,297,712	36,297,712	164,351	4,016,201	13,465,649	1,645,246	149,099,336	400,182,173	22,999,300	30,595,621	7,858,814	4,370,237	42,824,671	81,827,215	19,371,269	1,119,142	102,317,626	556,934,803
3.400	3.950	3.650	0.000	10	101,503	570,539	3,102,053	3,672,592	22,272,462	36,297,712	36,297,712	163,401	3,992,990	13,387,826	1,645,912	150,144,240	401,134,814	22,703,207	30,666,400	7,873,118	4,370,237	42,909,755	82,016,512	19,406,528	1,119,142	102,542,181	558,177,537
3.450	3.900	3.650	0.000	10	101,503	559,791	3,062,787	3,622,578	22,272,462	36,297,712	36,297,712	162,354	3,967,394	13,302,007	1,646,646	151,209,312	402,107,935	22,468,411	30,737,955	7,887,516	4,370,237	42,995,708	82,207,885	19,442,017	1,119,142	102,769,043	559,480,517
3.500	3.850	3.650	0.000	10	101,503	549,731	3,149,500	3,699,231	22,272,462	36,297,712	36,297,712	163,956	4,006,548	13,433,282	1,645,523	152,116,889	402,630,334	22,292,557	30,810,300	7,902,008	4,370,237	43,082,544	82,401,370	19,477,738	1,119,142	102,998,249	560,692,335
3.550	3.800	3.650	0.000	10	101,503	536,139	3,243,754	3,779,893	22,272,462	36,297,712	36,297,712	165,623	4,047,286	13,569,871	1,644,354	153,032,457	403,143,661	22,173,289	30,883,448	7,916,595	4,370,237	43,170,280	82,597,003	19,513,693	1,119,142	103,229,838	561,950,628
3.600	3.750	3.650	0.000	10	101,503	523,553	3,505,937	4,029,490	22,272,462	36,297,712	36,297,712	170,666	4,170,502	13,982,994	1,640,818	153,738,708	403,077,686	22,108,251	30,957,414	7,931,278	4,370,237	43,258,929	82,794,822	19,549,887	1,119,142	103,463,851	563,074,189

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)																		CO2 Emissions				WLC - Dual carriagway per km
						Maintenance over design life			Disruption time: Construction roadworks			Disruption time: Maintenance roadworks			Travel time during normal operations				Fuel Consumption								
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	
3.650	3.700	3.650	0.000	10	-	511,867	3,632,151	4,144,018	-	-	-	172,924	4,225,682	14,168,001	1,639,235	154,638,757	403,491,962	22,095,088	31,032,211	7,946,059	4,370,237	43,348,507	82,994,865	19,586,320	1,119,142	103,700,327	501,083,000
3.700	3.650	3.650	0.000	10	50,751	497,555	3,981,186	4,478,741	16,091,078	26,223,834	26,223,834	179,339	4,382,462	14,693,661	1,634,737	155,274,280	403,188,891	22,131,443	31,107,854	7,960,939	4,370,237	43,439,029	83,197,170	19,622,997	1,119,142	103,939,309	547,954,260
3.750	3.650	3.600	0.000	10	50,751	484,373	3,981,186	4,465,559	16,091,078	26,223,834	26,223,834	179,092	4,376,408	14,673,362	1,634,910	155,290,779	407,280,129	22,199,004	31,106,799	7,975,236	4,370,237	43,452,272	83,194,348	19,658,240	1,119,142	103,971,729	550,741,828
3.800	3.650	3.550	0.000	10	101,503	472,192	3,981,186	4,453,378	22,272,462	36,297,712	36,297,712	178,862	4,370,805	14,654,577	1,635,071	155,306,049	411,451,093	22,302,810	31,107,814	7,990,656	4,370,237	43,468,707	83,197,063	19,696,249	1,119,142	104,012,453	571,202,130
3.850	3.650	3.500	0.000	10	101,503	458,109	3,981,186	4,439,296	22,272,462	36,297,712	36,297,712	178,597	4,364,318	14,632,824	1,635,257	155,323,731	415,713,979	22,440,957	31,110,913	8,007,203	4,370,237	43,488,353	83,205,351	19,737,035	1,119,142	104,061,528	574,165,485
3.900	3.650	3.450	0.000	10	101,503	445,172	3,981,186	4,426,359	22,272,462	36,297,712	36,297,712	178,353	4,358,348	14,612,809	1,635,429	155,340,000	420,061,302	22,611,538	31,116,110	8,024,882	4,370,237	43,511,229	83,219,252	19,780,611	1,119,142	104,119,005	577,215,839
3.950	3.650	3.400	0.000	10	101,503	433,248	3,981,186	4,414,434	22,272,462	36,297,712	36,297,712	178,127	4,352,837	14,594,333	1,635,587	155,355,018	424,496,153	22,812,648	31,123,421	8,043,697	4,370,237	43,537,355	83,238,804	19,826,989	1,119,142	104,184,935	580,353,878
4.000	3.650	3.350	0.000	10	101,503	419,963	3,981,186	4,401,149	22,272,462	36,297,712	36,297,712	177,876	4,346,689	14,573,717	1,635,763	155,371,776	429,029,563	23,042,382	31,132,861	8,063,655	4,370,237	43,566,752	83,264,051	19,876,183	1,119,142	104,259,376	583,582,954
4.050	3.650	3.300	0.000	10	101,503	407,767	3,981,186	4,388,954	22,272,462	36,297,712	36,297,712	177,644	4,341,036	14,554,764	1,635,925	155,387,182	433,656,067	23,298,834	31,144,447	8,084,760	4,370,237	43,599,444	83,295,038	19,928,206	1,119,142	104,342,386	586,901,083
4.100	3.650	3.250	0.000	10	101,503	396,534	3,981,186	4,377,720	22,272,462	36,297,712	36,297,712	177,431	4,335,821	14,537,280	1,636,075	155,401,394	438,379,123	23,580,097	31,158,198	8,107,020	4,370,237	43,635,455	83,331,814	19,983,075	1,119,142	104,434,031	590,309,210
4.150	3.650	3.200	0.000	10	101,503	384,330	3,981,186	4,365,516	22,272,462	36,297,712	36,297,712	177,199	4,330,148	14,518,260	1,636,238	155,416,854	443,208,860	23,884,267	31,174,132	8,130,441	4,370,237	43,674,810	83,374,429	20,040,805	1,119,142	104,534,376	593,810,611
4.200	3.650	3.150	0.000	10	101,503	373,121	3,981,186	4,354,307	22,272,462	36,297,712	36,297,712	176,985	4,324,930	14,500,764	1,636,387	155,431,076	448,141,638	24,209,438	31,192,270	8,155,030	4,370,237	43,717,537	83,422,939	20,101,414	1,119,142	104,643,495	597,403,964
4.250	3.650	3.100	0.000	10	101,503	361,218	3,981,186	4,342,404	22,272,462	36,297,712	36,297,712	176,758	4,319,381	14,482,160	1,636,547	155,446,198	453,187,146	24,553,704	31,212,634	8,180,794	4,370,237	43,763,665	83,477,403	20,164,920	1,119,142	104,761,464	601,092,543
4.300	3.650	3.050	0.000	10	101,503	350,303	3,981,186	4,331,489	22,272,462	36,297,712	36,297,712	176,550	4,314,286	14,465,076	1,636,693	155,460,085	458,342,900	24,915,160	31,235,247	8,207,741	4,370,237	43,813,225	83,537,881	20,231,342	1,119,142	104,888,365	604,875,478
4.350	3.650	3.000	0.000	10	101,503	340,257	3,981,186	4,321,444	22,272,462	36,297,712	36,297,712	176,357	4,309,590	14,449,333	1,636,828	155,472,881	463,613,112	25,291,899	31,260,135	8,235,880	4,370,237	43,866,251	83,604,441	20,300,702	1,119,142	105,024,285	608,754,247
4.400	3.650	2.950	0.000	10	101,503	329,719	3,981,186	4,310,905	22,272,462	36,297,712	36,297,712	176,156	4,304,658	14,432,796	1,636,969	155,486,324	469,006,982	25,682,017	31,287,323	8,265,220	4,370,237	43,922,779	83,677,155	20,373,022	1,119,142	105,169,319	612,732,195
4.450	3.650	2.900	0.000	10	101,503	321,206	3,981,186	4,302,392	22,272,462	36,297,712	36,297,712	175,992	4,300,669	14,419,422	1,637,084	155,497,195	474,519,025	26,083,607	31,316,840	8,295,770	4,370,237	43,982,846	83,756,097	20,448,326	1,119,142	105,323,566	616,807,458
4.500	3.650	2.850	0.000	10	101,503	311,090	3,981,186	4,292,277	22,272,462	36,297,712	36,297,712	175,798	4,295,924	14,403,512	1,637,220	155,510,127	480,167,737	26,494,765	31,348,717	8,327,542	4,370,237	44,046,495	83,841,352	20,526,640	1,119,142	105,487,134	620,986,918
4.550	3.650	2.800	0.000	10	101,503	302,818	3,981,186	4,284,004	22,272,462	36,297,712	36,297,712	175,639	4,292,039	14,390,486	1,637,331	155,520,715	485,944,256	26,913,583	31,382,986	8,360,545	4,370,237	44,113,768	83,933,005	20,607,992	1,119,142	105,660,138	625,267,566
4.600	3.650	2.750	0.000	10	101,503	294,179	3,981,186	4,275,365	22,272,462	36,297,712	36,297,712	175,473	4,287,977	14,376,869	1,637,448	155,531,784	491,862,158	27,338,158	31,419,684	8,394,794	4,370,237	44,184,714	84,031,151	20,692,411	1,119,142	105,842,703	629,654,692
4.650	3.650	2.700	0.000	10	101,503	285,296	3,981,186	4,266,482	22,272,462	36,297,712	36,297,712	175,302	4,283,797	14,362,851	1,637,568	155,543,178	497,926,143	27,766,582	31,458,847	8,430,299	4,370,237	44,259,383	84,135,893	20,779,928	1,119,142	106,034,963	634,150,425
4.700	3.650	2.650	0.000	10	101,503	277,941	3,981,186	4,259,127	22,272,462	36,297,712	36,297,712	175,160	4,280,332	14,351,233	1,637,667	155,552,622	504,134,272	28,196,951	31,500,517	8,467,076	4,370,237	44,337,830	84,247,339	20,870,580	1,119,142	106,237,061	638,754,429
4.750	3.650	2.600	0.000	10	101,503	270,313	3,981,186	4,251,499	22,272,462	36,297,712	36,297,712	175,013	4,276,735	14,339,173	1,637,770	155,562,425	510,499,557	28,627,359	31,544,739	8,505,139	4,370,237	44,420,115	84,365,608	20,964,403	1,119,142	106,449,153	643,472,125
4.800	3.650	2.550	0.000	10	101,503	262,506	3,981,186	4,243,692	22,272,462	36,297,712	36,297,712	174,862	4,273,050	14,326,818	1,637,876	155,572,468	517,027,601	29,055,900	31,591,559	8,544,506	4,370,237	44,506,302	84,490,828	21,061,437	1,119,142	106,671,407	648,306,242
4.850	3.650	2.500	0.000	10	101,503	255,285	3,981,186	4,236,471	22,272,462	36,297,712	36,297,712	174,722	4,269,638	14,315,379	1,637,974	155,581,766	523,721,379	29,480,668	31,641,030	8,585,192	4,370,237	44,596,459	84,623,137	21,161,726	1,119,142	106,904,005	653,258,567
4.900	3.600	2.500	0.000	10	101,503	248,586	4,417,481	4,666,067	22,272,462	36,297,712	36,297,712	182,819	4,467,495	14,978,760	1,632,297	156,115,491	523,261,965	29,564,186	31,717,535	8,600,172	4,370,237	44,687,943	84,827,746	21,198,649	1,119,142	107,145,537	654,447,966
4.950	3.550	2.500	0.000	10	101,503	242,356	4,646,535	4,888,891	22,272,462	36,297,712	36,297,712	186,863	4,566,313	15,310,082	1,629,462	156,930,330	523,713,481	29,692,512	31,794,916	8,615,252	4,370,237	44,780,405	85,034,700	21,235,821	1,119,142	107,389,663	656,038,260
5.000	3.500	2.500	0.000	10	101,503	235,977	4,908,312	5,144,289	22,272,462	36,297,712	36,297,712	191,379	4,676,680	15,680,122	1,626,295	157,724,472	524,060,582	29,863,289	31,873,190	8,630,435	4,370,237	44,873,862	85,244,042	21,273,246	1,119,142	107,636,429	657,631,191
2.850	3.000	2.575	2.575	20	152,254	1,119,095	4,207,125	5,326,220	26,937,359	43,900,155	43,900,155	389,049	4,225,363	15,937,801	3,248,179	67,479,649	221,393,850	34,275,854	24,994,995	6,685,452	4,151,725	35,832,172	66,848,483	16,479,037	1,063,185	84,390,705	391,592,510
2.850	3.050	2.550	2.550	20	152,254	1,119,095	4,277,243	5,396,338	26,937,359	43,900,155	43,900,155	391,443	4,251,362	16,035,864	3,246,501	66,939,579	222,232,738	34,329,263	24,983,750	6,703,012	4,151,725	35,838,487	66,818,408	16,522,322	1,063,185	84,403,915	391,970,276
2.850	3.100	2.525	2.525	20	152,254	1,119,095	4,347,362	5,466,457	26,937,359	43,900,155	43,900,155	393,820	4,277,181	16,133,253	3,244,834	66,407,776	223,079,679	34,392,108	24,974,504	6,721,360	4,151,725	35,847,590	66,793,682	16,567,548	1,063,185	84,424,415	392,371,357
2.850	3.150	2.500	2.500	20	152,254	1,119,095	4,417,481	5,536,576	26,937,359	43,900,155	43,900,155	396,181	4,302,825	16,229,981	3,243,179	65,884,052	223,934,761	34,465,385	24,967,259	6,740,498	4,151,725	35,859,483	66,774,305	16,614,721	1,063,185	84,452,211	392,796,372
2.900	3.000	2.550	2.550	20	152,254	1,138,728	4,207,125	5,345,853	26,937,359	43,900,155	43,900,155	389,721	4,232,661	15,965,328	3,247,708	67,469,861	222,867,098	34,596,731	25,013,621	6,709,104	4,151,725	35,874,450	66,898,299	16,537,338	1,063,185	84,498,821	392,918,771
2.900	3.050	2.525	2.525	20	152,254	1,138,728	4,277,243	5,415,972	26,937,359	43,900,155	43,900,155	392,110	4,258,609	16,063,201	3,246,033	66,929,932	223,718,330	34,648,725	25,003,645	6,727,333	4,151,725	35,882,702	66,871,617	16,582,269	1,063,185	84,517,071	393,308,405
2.900	3.100	2.500	2.500	20	152,254	1,138,728	4,347,362	5,486,090	26,937,359	43,900,155	43,900,155	394,483	4,284,379	16,160,403	3,244,369	66,398,266	224,577,773	34,709,799	24,995,676	6,746,351	4,151,725	35,893,752	66,850,305	16,629,149	1,063,185	84,542,639	393,721,251
2.950	3.000	2.525	2.525	20	152,254	1,158,362	4,207,125	5,365,486	26,937,359	43,900,155	43,900,155	390,392	4,239,945	15,992,800	3,247,238	67,460,093	224,360,584	34,916,193	25,033,516	6,733,424	4,151,725	35,918,665	66,951,507	16,597,285	1,063,185	84,611,977	394,262,198
2.950	3.050	2.500	2.500	20	152,254	1,158,362	4,277,243	5,435,605	26,937,359	43,900,155	43,900,155	392,776	4,265,842	16,090,484	3,245,566	66,920,303	225,224,417	34,966,416	25,024,816	6,752,324	4,151,725	35,928,865	66,928,240	16,643,870	1,063,185	84,635,295	394,663,662
3.000	3.000	2.500	2.500	20	152,254	1,177,995	4,207,125	5,385,119	26,937,359	43,900,155	43,900,155	391,061	4,247,214	16,020,220	3,246,769	67,450,343	225,874,726	35,233,884	25,054,688	6,758,415	4,151,725	35,964,828	67,008,131	16,658,886	1,063,185	84,730,201	395,622,859
3.050	4.300	3.650	0.000	20	101,503	1,197,628	3,247,037	4,444,665	22,272,462	36,297,712	36,297,712	357,396	3,881,593	14,641,123	3,270,373	115,502,266	381,626,420	25,943,579	28,721,144	7,573,153	4,370,237	40,664,533	76,813,974	18,667,140	1,119,142	96,600,256	521,267,728
3.100	4.250	3.650	0.000	20	101,503	1,193,394	3,209,281	4,402,674	22,272,462	36,297,712	36,297,712	355,809	3,864,351	14,576,086	3,271,486	116,275,173	382,550,158	25,245,375	28,778,881	7,586,890	4,370,237	40,736,009	76,968,392	18,701,002	1,119,142	96,788,536	522,023,364
3.150	4.200	3.650	0.000	20	101,503	1,189,322	3,171,525	4,360,846	22,272,462	36,297,712	36,297,712	354,219	3,847,089	14,510,974	3,272,600	117,058,005	383,477,897	24,621,001	28,837,244	7,600,720	4,370,237	40,808,200	77,124,481	18,735,090	1,119,142	96,978,713	522,839,289
3.200	4.150	3.650	0.000	20	101,503	1,185,404	3,133,768	4,319,172	22,272,462	36,297,712	36,297,712	352,628	3,829,802	14,445,770	3,273,716	117,850,961	384,409,695	24,068,153	28,896,240	7,614,641	4,370,237	40,881,118	77,282,265	18,769,406	1,119,142	97,170,813	523,714,145
3.250	4.100	3.650	0.000	20	101,503	1,181,631	3,096,012	4,277,643	22,272,462	36,297,712	36,297,712	351,034	3,812,488	14,380,460	3,274,834	118,654,248	385,345,607	23,584,523	28,955,880	7,628,657	4,370,237	40,954,774	77,441,771	18,803,952	1,119,142	97,364,865	524,646,575
3.300	4.050	3.650	0.000	20	101,503	1,156,959	3,058,256	4,215,215	22,272,462	36,297,712	36,297,712	348,622	3,786,291	14,281,648	3,276,525	119,488,912	386,353,057	23,167,806	29,016,174	7,642,766	4,370,237	41,029,176	77,603,024	18,838,731	1,119,142	97,560,896	525,651,692
3.350	4.000	3.650	0.000	20	101,503	1,133,989	3,020,500	4,154,489	22,272,462	36,297,712	36,297,712	346,257	3,760,610	14,184,780	3,278,183	120,333,301	387,360,807	22,815,697	29,077,131	7,656,971	4,370,237	41,104,338	77,766,052	18,873,743	1,119,142	97,758,938	526,711,193
3.400	3.950	3.650	0.000	20	101,503	1,112,551	2,982,743	4,095,294	22,272,462	36,297,712	36,297,712	343,934	3,735,384	14,089,629	3,279,812	121,187,751	388,369,324	22,525,890	29,138,762	7,671,271	4,370,237	41,180,270	77,930,884	18,908,993	1,119,142	97,959,018	527,823,797
3.450	3.900	3.650	0.000	20	101,503	1,092,495	3,062,787	4,155,282	22,272,462	36,297,712	36,297,712	346,288	3,760,947	14,186,050	3,278,161	121,931,600	388,993,023	22,296,079	29,201,078	7,685,669	4,370,237	41,256,984	78,097,546	18,944,482	1,119,142	98,161,170	528,889,981
3.500	3.850	3.650	0.000	20	101,503	1,057,175	3,023,520	4,080,695	22,272,462	36,297,712	36,297,712	343,359	3,729,133	14,066,050	3,280,215	122,824,096	390,059,829	22,123,959	29,264,090	7,700,164	4,370,237	41,334,491	78,266,070	18,980,212	1,119,142	98,365,424	530,117,759
3.550	3.800	3.650	0.000	20	101,503	1,024,971	2,984,254	4,009,225	22,272,462	36,297,712	36,297,712	340,525	3,698,357	13,949,967	3,282,202	123,726,086	391,123,169	22,007,223	29,327,809	7,714,758	4,370,237	41,412,804	78,436,485	19,016,185	1,119,142	98,571,812	531,393,839
3.600	3.750	3.650	0.000	20	101,503	995,489	2,944,987	3,940,476	22,272,462	36,297,712	36,297,712	337,774	3,668,477	13,837,263	3,284,131	124,638,112	392,184,119	21,943,566	29,392,247	7,729,453	4,370,237	41,491,936	78,608,823	19,052,405	1,119,142	98,780,369	532,717,074
3.650	3.700	3.650	0.000	20	-	968,397	2,905,721	3,874,117	-	-	-	335,094	3,639,373	13,727,482	3,286,010	125,560,676	393,243,596	21,930,682	29,457,415	7,744,248	4,370,237	41,571,900	78,783,114	19,088,873	1,119,142	98,991,129	470,773,373
3.700	3.650	3.650	0.000	20	50,751	931,321	2,866,454	3,797,775	16,091,078	26,223,834	26,223,834	331,981	3,605,560	13,599,942	3,288,193	126,507,616	394,344,045	21,966,265	29,523,327	7,759,145	4,370,237	41,652,708	78,959,393	19,125,593	1,119,142	99,204,128	517,925,140
3.750	3.650	3.600	0.000	20	50,751	908,947	2,866,454	3,775,401	16,091,078	26,223,834	26,223,834	331,062	3,595,582	13,562,306	3,288,837	126,532,399	398,271,254	22,033,826	29,522,272	7,773,442	4,370,237	41,665,951	78,956,570	19,160,836	1,119,142	99,236,548	520,588,441
3.800	3.650	3.550	0.000	20	101,503	877,722	2,866,454	3,744,176	22,272,462	36,297,712	36,297,712	329,775	3,581,604	13,509,583	3,289,739	126,567,116	402,307,463	22,137,632	29,523,287	7,788,862	4,370,237	41,682,386	78,959,285	19,198,845	1,119,142	99,277,272	540,930,757
3.850	3.650	3.500	0.000	20	101,503	839,867	2,866,454	3,706,321	22,272,462	36,297,712	36,297,712	328,207	3,564,575	13,445,351	3,290,839	126,609,412	406,448,366	22,275,779	29,526,386	7,805,409	4,370,237	41,702,032	78,967,574	19,239,631	1,119,142	99,326,347	543,777,745
3.900	3.650	3.450	0.000	20	101,503	814,571	2,866,454	3,681,025	22,272,462	36,297,712	36,297,712	327,155	3,553,145	13,402,235	3,291,577	126,637,804	410,627,460	22,446,360	29,531,583	7,823,088	4,370,237	41,724,908	78,981,474	19,283,207	1,119,142	99,383,823	546,696,586
3.950	3.650	3.400	0.000	20	101,503	783,347	2,866,454	3,649,801	22,272,462	36,297,712	36,297,712	325,850	3,538,977	13,348,796	3,292,491	126,672,992	414,913,717	22,647,470	29,538,894	7,841,903	4,370,237	41,751,034	79,001,027	19,329,585	1,119,142	99,449,754	549,706,848
4.000	3.650	3.350	0.000	20	101,503	755,125	2,866,454	3,621,579	22,272,462	36,297,712	36,297,712	324,666	3,526,117	13,300,287	3,293,322	126,704,935	419,277,203	22,877,204	29,548,334	7,861,861	4,370,237	41,780,431	79,026,274	19,378,779	1,119,142	99,524,194	552,799,551
4.050	3.650	3.300	0.000	20	101,503	729,492	2,866,454	3,595,946	22,272,462	36,297,712	36,297,712	323,586	3,514,390	13,256,054	3,294,079	126,734,062	423,721,759	23,133,656	29,559,920	7,882,966	4,370,237	41,813,123	79,057,261	19,430,802	1,119,142	99,607,205	555,975,499
4.100	3.650	3.250	0.000	20	101,503	699,968	2,866,454	3,566,422	22,272,462	36,297,712	36,297,712	322,338	3,500,827	13,204,897	3,294,954	126,767,748	428,274,847	23,414,919	29,573,671	7,905,226	4,370,237	41,849,134	79,094,036	19,485,671	1,119,142	99,698,849	559,242,883
4.150	3.650	3.200	0.000	20	101,503	678,983	2,866,454	3,545,437	22,272,462	36,297,712	36,297,712	321,447	3,491,151	13,168,400	3,295,579	126,791,781	432,891,392	23,719,089	29,589,605	7,928,647	4,370,237	41,888,489	79,136,652	19,543,401	1,119,142	99,799,195	562,587,566
4.200	3.650	3.150	0.000	20	101,503	654,442	2,866,454	3,520,896	22,272,462	36,297,712	36,297,712	320,401	3,479,797	13,125,571	3,296,312	126,819,984	437,621,129	24,044,260	29,607,743	7,953,236	4,370,237	41,931,216	79,185,162	19,604,010	1,119,142	99,908,314	566,024,845
4.250	3.650	3.100	0.000	20	101,503	632,131	2,866,454	3,498,585	22,272,462	36,297,712	36,297,712	319,447	3,469,438	13,086,497	3,296,981	126,845,713	442,444,561	24,388,526	29,628,107	7,979,000	4,370,237	41,977,344	79,239,625	19,667,516	1,119,142	100,026,283	569,548,509
4.300	3.650	3.050	0.000	20	101,503	607,359	2,866,454	3,473,814	22,272,462	36,297,712	36,297,712	318,385	3,457,895	13,042,959	3,297,726	126,874,383	447,383,852	24,749,982	29,650,720	8,005,947	4,370,237	42,026,904	79,300,103	19,733,938	1,119,142	100,153,183	573,165,647
4.350	3.650	3.000	0.000	20	101,503	588,997	2,866,454	3,455,452	22,272,462	36,297,712	36,297,712	317,594	3,449,310	13,010,579	3,298,280	126,895,705	452,406,164	25,126,721	29,675,608	8,034,086	4,370,237	42,079,930	79,366,664	19,803,298	1,119,142	100,289,104	576,865,485
4.400	3.650	2.950	0.000	20	101,503	568,331	2,866,454	3,434,785	22,272,462	36,297,712	36,297,712	316,702	3,439,620	12,974,026	3,298,906	126,919,774	457,550,678	25,516,839	29,702,796	8,063,426	4,370,237	42,136,458	79,439,377	19,875,618	1,119,142	100,434,137	580,660,876
4.450	3.650	2.900	0.000	20	101,503	546,050	2,866,454	3,412,504	22,272,462	36,297,712	36,297,712	315,737	3,429,137	12,934,486	3,299,583	126,945,811	462,818,691	25,918,429	29,732,313	8,093,976	4,370,237	42,196,525	79,518,320	19,950,922	1,119,142	100,588,384	584,552,450
4.500	3.650	2.850	0.000	20	101,503	529,040	2,866,454	3,395,494	22,272,462	36,297,712	36,297,712	314,998	3,421,110	12,904,207	3,300,101	126,965,749	468,184,698	26,329,587	29,764,190	8,125,748	4,370,237	42,260,174	79,603,574	20,029,236	1,119,142	100,751,952	588,531,638
4.550	3.650	2.800	0.000	20	101,503	510,464	2,866,454	3,376,919	22,272,462	36,297,712	36,297,712	314,188	3,412,320	12,871,051	3,300,668	126,987,582	473,681,918	26,748,405	29,798,459	8,158,751	4,370,237	42,327,447	79,695,227	20,110,588	1,119,142	100,924,957	592,609,896
4.600	3.650	2.750	0.000	20	101,503	496,225	2,866,454	3,362,679	22,272,462	36,297,712	36,297,712	313,566	3,405,564	12,845,568	3,301,104	127,004,362	479,288,737	27,172,980	29,835,157	8,193,000	4,370,237	42,398,393	79,793,374	20,195,007	1,119,142	101,107,522	596,779,909
4.650	3.650	2.700	0.000	20	101,503	480,498	2,866,454	3,346,952	22,272,462	36,297,712	36,297,712	312,877	3,398,084	12,817,357	3,301,587	127,022,939	485,035,205	27,601,404	29,874,320	8,228,505	4,370,237	42,473,062	79,898,115	20,282,525	1,119,142	101,299,782	601,052,425
4.700	3.650	2.650	0.000	20	101,503	463,700	2,866,454	3,330,154	22,272,462	36,297,712	36,297,712	312,140	3,390,075	12,787,146	3,302,104	127,042,833	490,924,484	28,031,773	29,915,990	8,265,282	4,370,237	42,551,509	80,009,562	20,373,176	1,119,142	101,501,880	605,428,991

Appendix A

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)	Maintenance over design life			Disruption time: Construction roadwork			Disruption time: Maintenance roadwork			Travel time during normal operations				Fuel Consumption				CO2 Emissions				
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	WLC - Dual carriagway per km
4.750	3.650	2.600	0.000	20	101,503	450,521	2,866,454	3,316,976	22,272,462	36,297,712	36,297,712	311,560	3,383,776	12,763,388	3,302,511	127,058,477	496,940,005	28,462,181	29,960,212	8,303,345	4,370,237	42,633,794	80,127,831	20,466,999	1,119,142	101,713,972	609,904,018
4.800	3.650	2.550	0.000	20	101,503	436,294	2,866,454	3,302,749	22,272,462	36,297,712	36,297,712	310,933	3,376,962	12,737,684	3,302,951	127,075,403	503,108,314	28,890,722	30,007,032	8,342,712	4,370,237	42,719,981	80,253,050	20,564,033	1,119,142	101,936,225	614,487,540
4.850	3.650	2.500	0.000	20	101,503	423,206	2,866,454	3,289,660	22,272,462	36,297,712	36,297,712	310,354	3,370,679	12,713,984	3,303,357	127,091,009	509,424,681	29,315,490	30,056,503	8,383,398	4,370,237	42,810,138	80,385,359	20,664,322	1,119,142	102,168,823	619,178,375
4.900	3.600	2.500	0.000	20	101,503	411,124	2,944,987	3,356,111	22,272,462	36,297,712	36,297,712	313,279	3,402,442	12,833,794	3,301,306	127,891,088	510,508,465	29,397,235	30,123,170	8,398,398	4,370,237	42,891,805	80,563,658	20,701,296	1,119,142	102,384,096	620,832,674
4.950	3.550	2.500	0.000	20	101,503	398,297	3,030,349	3,428,647	22,272,462	36,297,712	36,297,712	316,436	3,436,735	12,963,146	3,299,092	128,695,947	511,572,903	29,522,836	30,190,606	8,413,503	4,370,237	42,974,345	80,744,013	20,738,527	1,119,142	102,601,681	622,520,772
5.000	3.500	2.500	0.000	20	101,503	386,481	3,123,471	3,509,953	22,272,462	36,297,712	36,297,712	319,934	3,474,720	13,106,422	3,296,640	129,502,741	512,606,172	29,689,988	30,258,823	8,428,712	4,370,237	43,057,772	80,926,458	20,776,017	1,119,142	102,821,616	624,236,896
2.850	3.000	2.575	2.575	30	152,254	1,512,291	4,207,125	5,719,415	26,937,359	43,900,155	43,900,155	603,397	3,822,782	16,479,187	4,858,370	56,192,018	217,370,945	34,027,732	24,617,223	6,648,900	4,151,725	35,417,848	65,838,141	16,388,941	1,063,185	83,290,267	381,781,256
2.850	3.050	2.550	2.550	30	152,254	1,512,291	3,992,094	5,504,384	26,937,359	43,900,155	43,900,155	592,649	3,754,689	16,185,655	4,865,906	55,857,614	218,606,093	34,091,028	24,612,119	6,666,959	4,151,725	35,430,803	65,824,491	16,433,454	1,063,185	83,321,129	382,066,582
2.850	3.100	2.525	2.525	30	152,254	1,512,291	3,803,942	5,316,233	26,937,359	43,900,155	43,900,155	583,060	3,693,940	15,923,778	4,872,629	55,518,922	219,814,809	34,163,360	24,608,973	6,685,814	4,151,725	35,446,512	65,816,078	16,479,930	1,063,185	83,359,192	382,388,238
2.850	3.150	2.500	2.500	30	152,254	1,512,291	3,254,986	4,767,277	26,937,359	43,900,155	43,900,155	554,005	3,509,865	15,130,269	4,893,001	55,339,596	221,651,863	34,245,672	24,607,787	6,705,468	4,151,725	35,464,980	65,812,906	16,528,376	1,063,185	83,404,466	382,567,277
2.900	3.000	2.550	2.550	30	152,254	1,581,567	4,207,125	5,788,692	26,937,359	43,900,155	43,900,155	606,813	3,844,429	16,572,502	4,855,974	56,164,310	218,718,401	34,348,609	24,635,849	6,672,553	4,151,725	35,460,127	65,887,957	16,447,242	1,063,185	83,398,384	383,098,775
2.900	3.050	2.525	2.525	30	152,254	1,581,567	3,992,094	5,573,661	26,937,359	43,900,155	43,900,155	596,135	3,776,778	16,280,876	4,863,461	55,829,551	219,965,234	34,410,491	24,632,014	6,691,279	4,151,725	35,475,018	65,877,699	16,493,401	1,063,185	83,434,285	383,396,942
2.900	3.100	2.500	2.500	30	152,254	1,581,567	3,803,942	5,385,509	26,937,359	43,900,155	43,900,155	586,611	3,716,438	16,020,763	4,870,139	55,490,552	221,185,721	34,481,050	24,630,145	6,710,805	4,151,725	35,492,675	65,872,701	16,541,530	1,063,185	83,477,416	383,731,198
2.950	3.000	2.525	2.525	30	152,254	1,608,836	4,207,125	5,815,960	26,937,359	43,900,155	43,900,155	608,152	3,852,911	16,609,070	4,855,035	56,153,451	220,150,083	34,668,071	24,655,744	6,696,873	4,151,725	35,504,342	65,941,165	16,507,189	1,063,185	83,511,539	384,412,359
2.950	3.050	2.500	2.500	30	152,254	1,608,836	3,992,094	5,600,929	26,937,359	43,900,155	43,900,155	597,501	3,785,433	16,318,185	4,862,503	55,818,556	221,410,475	34,728,181	24,653,186	6,716,270	4,151,725	35,521,181	65,934,323	16,555,002	1,063,185	83,552,509	384,723,584
3.000	3.000	2.500	2.500	30	152,254	1,636,104	4,207,125	5,843,229	26,937,359	43,900,155	43,900,155	609,488	3,861,373	16,645,546	4,854,099	56,142,620	221,601,303	34,985,762	24,676,916	6,721,864	4,151,725	35,550,505	65,997,788	16,568,790	1,063,185	83,629,763	385,742,407
3.050	4.300	3.650	0.000	30	101,503	1,663,372	3,247,037	4,910,410	22,272,462	36,297,712	36,297,712	561,745	3,558,900	15,341,650	4,887,574	91,944,503	368,687,667	25,692,132	27,459,731	7,376,572	4,370,237	39,206,540	73,440,358	18,182,586	1,119,142	92,742,086	495,001,730
3.100	4.250	3.650	0.000	30	101,503	1,690,641	3,209,281	4,899,922	22,272,462	36,297,712	36,297,712	561,182	3,555,333	15,326,273	4,887,969	92,535,748	369,531,759	25,009,072	27,509,502	7,390,200	4,370,237	39,269,938	73,573,468	18,216,178	1,119,142	92,908,788	495,636,916
3.150	4.200	3.650	0.000	30	101,503	1,717,909	3,171,525	4,889,434	22,272,462	36,297,712	36,297,712	560,618	3,551,762	15,310,879	4,888,364	93,134,559	370,379,622	24,398,241	27,559,832	7,403,926	4,370,237	39,333,995	73,708,075	18,250,012	1,119,142	93,077,228	496,329,394
3.200	4.150	3.650	0.000	30	101,503	1,698,011	3,133,768	4,831,779	22,272,462	36,297,712	36,297,712	557,508	3,532,058	15,225,938	4,890,545	93,775,307	371,366,829	23,857,384	27,610,730	7,417,751	4,370,237	39,398,718	73,844,201	18,284,088	1,119,142	93,247,431	497,101,924
3.250	4.100	3.650	0.000	30	101,503	1,724,542	3,096,012	4,820,554	22,272,462	36,297,712	36,297,712	556,900	3,528,207	15,209,339	4,890,971	94,390,489	372,224,897	23,384,244	27,662,205	7,431,675	4,370,237	39,464,116	73,981,868	18,318,410	1,119,142	93,419,420	497,905,684
3.300	4.050	3.650	0.000	30	101,503	1,704,993	3,058,256	4,763,249	22,272,462	36,297,712	36,297,712	553,786	3,508,474	15,124,272	4,893,155	95,047,830	373,220,862	22,976,566	27,714,263	7,445,699	4,370,237	39,530,199	74,121,097	18,352,979	1,119,142	93,593,218	498,787,332
3.350	4.000	3.650	0.000	30	101,503	1,686,446	3,020,500	4,706,945	22,272,462	36,297,712	36,297,712	550,706	3,488,962	15,040,162	4,895,314	95,713,312	374,219,397	22,632,095	27,766,914	7,459,825	4,370,237	39,596,976	74,261,911	18,387,797	1,119,142	93,768,849	499,721,404
3.400	3.950	3.650	0.000	30	101,503	1,628,123	2,982,743	4,610,866	22,272,462	36,297,712	36,297,712	545,405	3,455,378	14,895,390	4,899,031	96,418,230	375,341,723	22,348,574	27,820,166	7,474,052	4,370,237	39,664,455	74,404,332	18,422,866	1,119,142	93,946,340	500,729,854
3.450	3.900	3.650	0.000	30	101,503	1,612,731	2,944,987	4,557,718	22,272,462	36,297,712	36,297,712	542,447	3,436,641	14,814,617	4,901,105	97,099,964	376,342,916	22,123,748	27,874,028	7,488,382	4,370,237	39,732,647	74,548,386	18,458,188	1,119,142	94,125,715	501,764,605
3.500	3.850	3.650	0.000	30	101,503	1,561,736	2,907,231	4,468,967	22,272,462	36,297,712	36,297,712	537,467	3,405,091	14,678,612	4,904,596	97,819,099	377,457,739	21,955,360	27,928,510	7,502,816	4,370,237	39,801,562	74,694,095	18,493,765	1,119,142	94,307,002	502,869,923
3.550	3.800	3.650	0.000	30	101,503	1,515,175	2,869,475	4,384,649	22,272,462	36,297,712	36,297,712	532,687	3,374,808	14,548,067	4,907,948	98,545,104	378,566,774	21,841,156	27,983,620	7,517,354	4,370,237	39,871,210	74,841,485	18,529,600	1,119,142	94,490,227	504,021,346
3.600	3.750	3.650	0.000	30	101,503	1,472,494	2,831,718	4,304,212	22,272,462	36,297,712	36,297,712	528,082	3,345,628	14,422,282	4,911,177	99,278,484	379,671,372	21,778,880	28,039,368	7,531,997	4,370,237	39,941,602	74,990,582	18,565,695	1,119,142	94,675,418	505,217,684
3.650	3.700	3.650	0.000	30	-	1,433,227	2,793,962	4,227,189	-	-	-	523,628	3,317,415	14,300,661	4,914,300	100,019,699	380,772,687	21,766,275	28,095,764	7,546,747	4,370,237	40,012,747	75,141,412	18,602,051	1,119,142	94,862,605	443,144,805
3.700	3.650	3.650	0.000	30	50,751	1,396,981	2,756,206	4,153,187	16,091,078	26,223,834	26,223,834	519,309	3,290,050	14,182,695	4,917,328	100,769,180	381,871,710	21,801,087	28,152,818	7,561,604	4,370,237	40,084,659	75,294,002	18,638,672	1,119,142	95,051,816	490,153,679
3.750	3.650	3.600	0.000	30	50,751	1,338,631	2,756,206	4,094,837	16,091,078	26,223,834	26,223,834	515,874	3,268,290	14,088,891	4,919,737	100,818,531	385,680,041	21,868,648	28,151,763	7,575,901	4,370,237	40,097,901	75,291,179	18,673,915	1,119,142	95,084,236	492,684,321
3.800	3.650	3.550	0.000	30	101,503	1,286,316	2,756,206	4,042,522	22,272,462	36,297,712	36,297,712	512,773	3,248,640	14,004,185	4,921,911	100,863,096	389,542,768	21,972,454	28,152,778	7,591,321	4,370,237	40,114,336	75,293,895	18,711,924	1,119,142	95,124,960	512,878,023
3.850	3.650	3.500	0.000	30	101,503	1,239,148	2,756,206	3,995,354	22,272,462	36,297,712	36,297,712	509,958	3,230,807	13,927,310	4,923,885	100,903,541	393,464,070	22,110,601	28,155,877	7,607,868	4,370,237	40,133,982	75,302,183	18,752,710	1,119,142	95,174,035	515,561,954
3.900	3.650	3.450	0.000	30	101,503	1,196,401	2,756,206	3,952,607	22,272,462	36,297,712	36,297,712	507,392	3,214,549	13,857,225	4,925,684	100,940,413	397,447,817	22,281,182	28,161,075	7,625,547	4,370,237	40,156,858	75,316,084	18,796,286	1,119,142	95,231,512	518,323,085
3.950	3.650	3.400	0.000	30	101,503	1,157,483	2,756,206	3,913,689	22,272,462	36,297,712	36,297,712	505,042	3,199,665	13,793,066	4,927,331	100,974,169	401,497,664	22,482,292	28,168,385	7,644,362	4,370,237	40,182,984	75,335,636	18,842,664	1,119,142	95,297,442	521,161,822
4.000	3.650	3.350	0.000	30	101,503	1,106,098	2,756,206	3,862,304	22,272,462	36,297,712	36,297,712	501,922	3,179,894	13,707,835	4,929,519	101,019,010	405,672,621	22,712,026	28,177,825	7,664,320	4,370,237	40,212,382	75,360,883	18,891,858	1,119,142	95,371,883	524,092,523
4.050	3.650	3.300	0.000	30	101,503	1,060,195	2,756,206	3,816,401	22,272,462	36,297,712	36,297,712	499,115	3,162,113	13,631,185	4,931,487	101,059,336	409,913,184	22,968,478	28,189,412	7,685,425	4,370,237	40,245,074	75,391,870	18,943,882	1,119,142	95,454,893	527,100,436
4.100	3.650	3.250	0.000	30	101,503	1,018,941	2,756,206	3,775,147	22,272,462	36,297,712	36,297,712	496,577	3,146,035	13,561,878	4,933,267	101,095,800	414,224,017	23,249,741	28,203,162	7,707,685	4,370,237	40,281,084	75,428,646	18,998,750	1,119,142	95,546,538	530,186,314
4.150	3.650	3.200	0.000	30	101,503	981,662	2,756,206	3,737,868	22,272,462	36,297,712	36,297,712	494,272	3,131,427	13,498,904	4,934,883	101,128,931	418,609,482	23,553,911	28,219,096	7,731,106	4,370,237	40,320,439	75,471,261	19,056,481	1,119,142	95,646,884	533,350,926
4.200	3.650	3.150	0.000	30	101,503	947,812	2,756,206	3,704,018	22,272,462	36,297,712	36,297,712	492,167	3,118,094	13,441,432	4,936,359	101,159,168	423,073,730	23,879,082	28,237,235	7,755,695	4,370,237	40,363,166	75,519,771	19,117,089	1,119,142	95,756,002	536,595,071
4.250	3.650	3.100	0.000	30	101,503	906,971	2,756,206	3,663,177	22,272,462	36,297,712	36,297,712	489,615	3,101,922	13,371,718	4,938,149	101,195,841	427,658,686	24,223,348	28,257,599	7,781,459	4,370,237	40,409,294	75,574,234	19,180,595	1,119,142	95,873,971	539,930,075
4.300	3.650	3.050	0.000	30	101,503	879,406	2,756,206	3,635,612	22,272,462	36,297,712	36,297,712	487,883	3,090,953	13,324,432	4,939,363	101,220,723	432,290,279	24,584,804	28,280,212	7,808,406	4,370,237	40,458,854	75,634,713	19,247,018	1,119,142	96,000,872	543,335,442
4.350	3.650	3.000	0.000	30	101,503	845,590	2,756,206	3,601,796	22,272,462	36,297,712	36,297,712	485,750	3,077,436	13,266,163	4,940,859	101,251,378	437,045,883	24,961,543	28,305,099	7,836,545	4,370,237	40,511,881	75,701,273	19,316,378	1,119,142	96,136,792	546,832,580
4.400	3.650	2.950	0.000	30	101,503	814,965	2,756,206	3,571,171	22,272,462	36,297,712	36,297,712	483,808	3,065,136	13,213,140	4,942,220	101,279,275	441,892,267	25,351,661	28,332,287	7,865,885	4,370,237	40,568,408	75,773,986	19,388,698	1,119,142	96,281,826	550,412,200
4.450	3.650	2.900	0.000	30	101,503	780,071	2,756,206	3,536,277	22,272,462	36,297,712	36,297,712	481,585	3,051,053	13,152,432	4,943,778	101,311,214	446,862,413	25,753,251	28,361,804	7,896,435	4,370,237	40,628,476	75,852,929	19,464,002	1,119,142	96,436,073	554,083,961
4.500	3.650	2.850	0.000	30	101,503	755,125	2,756,206	3,511,331	22,272,462	36,297,712	36,297,712	479,989	3,040,940	13,108,835	4,944,898	101,334,151	451,902,245	26,164,409	28,393,681	7,928,207	4,370,237	40,692,124	75,938,183	19,542,316	1,119,142	96,599,641	557,831,967
4.550	3.650	2.800	0.000	30	101,503	726,271	2,756,206	3,482,477	22,272,462	36,297,712	36,297,712	478,135	3,029,194	13,058,203	4,946,198	101,360,789	457,071,387	26,583,227	28,427,951	7,961,210	4,370,237	40,759,398	76,029,836	19,623,667	1,119,142	96,772,645	561,674,028
4.600	3.650	2.750	0.000	30	101,503	705,570	2,756,206	3,461,776	22,272,462	36,297,712	36,297,712	476,800	3,020,736	13,021,741	4,947,134	101,379,972	462,323,344	27,007,802	28,464,648	7,995,459	4,370,237	40,830,343	76,127,983	19,708,086	1,119,142	96,955,210	565,596,165
4.650	3.650	2.700	0.000	30	101,503	676,256	2,756,206	3,432,462	22,272,462	36,297,712	36,297,712	474,902	3,008,712	12,969,910	4,948,464	101,407,241	467,732,638	27,436,226	28,503,812	8,030,964	4,370,237	40,905,012	76,232,725	19,795,604	1,119,142	97,147,470	569,621,618
4.700	3.650	2.650	0.000	30	101,503	654,442	2,756,206	3,410,648	22,272,462	36,297,712	36,297,712	473,484	2,999,729	12,931,185	4,949,459	101,427,626	473,234,825	27,866,595	28,545,482	8,067,741	4,370,237	40,983,460	76,344,171	19,886,256	1,119,142	97,349,568	573,730,637
4.750	3.650	2.600	0.000	30	101,503	634,408	2,756,206	3,390,614	22,272,462	36,297,712	36,297,712	472,178	2,991,452	12,895,506	4,950,375	101,446,386	478,858,151	28,297,003	28,589,703	8,105,804	4,370,237	41,065,744	76,462,440	19,980,078	1,119,142	97,561,660	577,932,305
4.800	3.650	2.550	0.000	30	101,503	611,945	2,756,206	3,368,151	22,272,462	36,297,712	36,297,712	470,708	2,982,141	12,855,368	4,951,405	101,467,503	484,625,772	28,725,544	28,636,524	8,145,171	4,370,237	41,151,931	76,587,660	20,077,112	1,119,142	97,783,914	582,234,551
4.850	3.650	2.500	0.000	30	101,503	591,436	2,756,206	3,347,642	22,272,462	36,297,712	36,297,712	469,362	2,973,611	12,818,596	4,952,349	101,486,849	490,522,975	29,150,312	28,685,995	8,185,857	4,370,237	41,242,089	76,719,969	20,177,401	1,119,142	98,016,512	586,633,124
4.900	3.600	2.500	0.000	30	101,503	576,065	2,827,188	3,403,253	22,272,462	36,297,712	36,297,712	473,067	2,996,965	12,918,029	4,949,796	102,136,502	491,692,840	29,230,284	28,743,717	8,200,823	4,370,237	41,314,777	76,874,347	20,214,289	1,119,142	98,207,778	588,194,885
4.950	3.550	2.500	0.000	30	101,503	555,340	2,787,921	3,343,262	22,272,462	36,297,712	36,297,712	469,073	2,971,786	12,810,726	4,952,551	102,905,492	493,398,279	29,353,161	28,802,120	8,215,897	4,370,237	41,388,253	77,030,542	20,251,447	1,119,142	98,401,131	589,975,402
5.000	3.500	2.500	0.000	30	101,503	539,375	2,748,655	3,288,030	22,272,462	36,297,712	36,297,712	465,423	2,948,658	12,711,029	4,955,111	103,681,189	495,094,166	29,516,687	28,861,212	8,231,082	4,370,237	41,462,531	77,188,583	20,288,876	1,119,142	98,596,601	591,792,542
2.850	3.000	2.575	2.575	40	152,254	2,152,106	2,560,858	4,712,964	26,937,359	43,900,155	43,900,155	734,715	2,992,332	15,049,179	6,526,777	46,600,951	216,002,981	33,779,610	24,309,428	6,619,817	4,151,725	35,080,970	65,014,952	16,317,253	1,063,185	82,395,390	372,510,529
2.850	3.050	2.550	2.550	40	152,254	2,152,106	2,395,256	4,547,362	26,937,359	43,900,155	43,900,155	722,492	2,942,551	14,798,820	6,535,347	46,312,613	217,143,790	33,852,794	24,309,804	6,638,377	4,151,725	35,099,906	65,015,958	16,363,002	1,063,185	82,442,144	372,858,495
2.850	3.100	2.525	2.525	40	152,254	2,152,106	2,434,523	4,586,629	26,937,359	43,900,155	43,900,155	725,411	2,954,441	14,858,616	6,533,300	45,953,886	217,939,516	33,934,611	24,312,095	6,657,743	4,151,725	35,121,562	65,022,084	16,410,736	1,063,185	82,496,005	373,329,267
2.850	3.150	2.500	2.500	40	152,254	2,152,106	2,473,789	4,625,895	26,937,359	43,900,155	43,900,155	728,317	2,966,276	14,918,140	6,531,263	45,600,518	218,741,911	34,025,958	24,316,303	6,677,916	4,151,725	35,145,944	65,033,340	16,460,462	1,063,185	82,556,987	373,820,756
2.900	3.000	2.550	2.550	40	152,254	2,189,862	2,560,858	4,750,721	26,937,359	43,900,155	43,900,155	737,469	3,003,551	15,105,603	6,524,846	46,587,161	217,364,830	34,100,487	24,328,055	6,643,469	4,151,725	35,123,249	65,064,768	16,375,554	1,063,185	82,503,507	373,794,230
2.900	3.050	2.525	2.525	40	152,254	2,189,862	2,395,256	4,585,119	26,937,359	43,900,155	43,900,155	725,299	2,953,984	14,856,321	6,533,379	46,298,665	218,517,400	34,172,256	24,329,699	6,662,697	4,151,725	35,144,121	65,069,166	16,422,949	1,063,185	82,555,300	374,154,511
2.900	3.100	2.500	2.500	40	152,254	2,189,862	2,434,523	4,624,385	26,937,359	43,900,155	43,900,155	728,206	2,965,822	14,915,856	6,531,341	45,940,104	219,324,224	34,252,301	24,333,267	6,682,734	4,151,725	35,167,725	65,078,708	16,472,337	1,063,185	82,614,229	374,636,078
2.950	3.000	2.525	2.525	40	152,254	2,227,619	2,560,858	4,788,477	26,937,359	43,900,155	43,900,155	740,212	3,014,723	15,161,789	6,522,922	46,573,429	218,745,054	34,419,949	24,347,949	6,667,790	4,151,725	35,167,464	65,117,976	16,435,501	1,063,185	82,616,662	375,093,736
2.950	3.050	2.500	2.500	40	152,254	2,227,619	2,395,256	4,622,875	26,937,359	43,900,155	43,900,155	728,094	2,965,368	14,913,571	6,531,419	46,284,777	219,909,632	34,489,946	24,350,871	6,687,688	4,151,725	35,190,284	65,125,789	16,484,550	1,063,185	82,673,524	375,466,276
3.000	3.000	2.500	2.500	40	152,254	2,265,375	2,560,858	4,826,233	26,937,359	43,900,155	43,900,155	742,944	3,025,848	15,217,740	6,521,007	46,559,754	220,144,019	34,737,640	24,369,121	6,692,781	4,151,725	35,213,627	65,174,600	16,497,102	1,063,185	82,734,886	376,409,080
3.050	4.300	3.650	0.000	40	101,503	2,303,131	2,281,702	4,584,833	22,272,462	36,297,712	36,297,712	720,786	2,953,898	14,855,887	6,533,394	72,322,565	358,063,041	25,440,684	26,386,846	7,187,632	4,370,237	37,944,714	70,570,954	17,716,865	1,119,142	89,406,960	471,867,096
3.100	4.250	3.650	0.000	40	101,503	2,340,887	2,255,170	4,596,058	22,272,462	36,297,712	36,297,712	726,110	2,957,288	14,872,934	6,532,810	72,775,254	358,867,975	24,772,769	26,429,169	7,201,038	4,370,237	38,000,443	70,684,145	17,749,909	1,119,142	89,553,196	472,416,149
3.150	4.200	3.650	0.000	40	101,503	2,290,546	2,228,639	4,519,185	22,272,462	36,297,712	36,297,712	720,389	2,933,986	14,755,741	6,536,822	73,285,244	359,929,697	24,175,481	26,472,000	7,214,550	4,370,237	38,056,787	70,798,697	17,783,216	1,119,142	89,701,054	473,055,849
3.200	4.150	3.650	0.000	40	101,503	2,243,800	2,202,108	4,445,907	22,272,462	36,297,712	36,297,712	714,887	2,911,577	14,643,041	6,540,680	73,800,059	360,987,919	23,646,615	26,515,347	7,228,169	4,370,237	38,113,753	70,914,627	17,816,785	1,119,142	89,850,555	473,749,587
3.250	4.100	3.650	0.000	40	101,503	2,200,278	2,299,895	4,500,173	22,272,462	36,297,712	36,297,712	718,966	2,928,190	14,726,595	6,537,820	74,245,247	361,679,479	23,183,966	26,559,216	7,241,895	4,370,237	38,171,349	71,031,954	17,850,620	1,119,142	90,001,716	474,441,925
3.300	4.050	3.650	0.000	40	101,503	2,159,657	2,338,666	4,498,324	22,272,462	36,297,712	36,297,712	718,827	2,927,626	14,723,757	6,537,917	74,730,037	362,538,288	22,785,327	26,603,614	7,255,730	4,370,237	38,229,581	71,150,695	17,884,722	1,119,142	90,154,558	475,209,087

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)	Maintenance over design life			isruption time: Construction roadwork			sruption time: Maintenance roadwo			Travel time during normal operations				Fuel Consumption				CO2 Emissions				
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	WLC - Dual carriageway per km
3.350	4.000	3.650	0.000	40	101,503	2,121,657	2,309,794	4,431,451	22,272,462	36,297,712	36,297,712	713,795	2,907,133	14,620,692	6,541,445	75,260,659	363,591,856	22,448,492	26,648,548	7,269,674	4,370,237	38,288,458	71,270,868	17,919,092	1,119,142	90,309,102	476,054,982
3.400	3.950	3.650	0.000	40	101,503	2,086,033	2,350,040	4,436,073	22,272,462	36,297,712	36,297,712	714,144	2,908,554	14,627,841	6,541,200	75,754,593	364,440,224	22,171,257	26,694,024	7,283,728	4,370,237	38,347,988	71,392,493	17,953,733	1,119,142	90,465,368	476,917,754
3.450	3.900	3.650	0.000	40	101,503	1,992,197	2,392,802	4,384,999	22,272,462	36,297,712	36,297,712	710,276	2,892,801	14,548,612	6,543,912	76,289,561	365,457,752	21,951,416	26,740,050	7,297,892	4,370,237	38,408,178	71,515,589	17,988,647	1,119,142	90,623,377	477,853,515
3.500	3.850	3.650	0.000	40	101,503	1,963,325	2,519,600	4,482,925	22,272,462	36,297,712	36,297,712	717,672	2,922,921	14,700,096	6,538,727	76,739,000	366,038,024	21,786,762	26,786,633	7,312,167	4,370,237	38,469,038	71,640,175	18,023,834	1,119,142	90,783,151	478,765,137
3.550	3.800	3.650	0.000	40	101,503	1,883,731	2,664,512	4,548,243	22,272,462	36,297,712	36,297,712	722,557	2,942,818	14,800,164	6,535,301	77,215,287	366,719,830	21,675,090	26,833,782	7,326,555	4,370,237	38,530,574	71,766,274	18,059,299	1,119,142	90,944,714	479,735,978
3.600	3.750	3.650	0.000	40	101,503	1,812,300	2,726,840	4,539,140	22,272,462	36,297,712	36,297,712	721,879	2,940,055	14,786,264	6,535,777	77,744,438	367,624,335	21,614,194	26,881,504	7,341,056	4,370,237	38,592,797	71,893,905	18,095,041	1,119,142	91,108,088	480,784,236
3.650	3.700	3.650	0.000	40	-	1,747,838	2,793,962	4,541,800	-	-	-	722,077	2,940,863	14,790,328	6,535,638	78,273,449	368,498,510	21,601,869	26,929,807	7,355,670	4,370,237	38,655,714	72,023,090	18,131,065	1,119,142	91,273,296	418,555,696
3.700	3.650	3.650	0.000	40	50,751	1,689,373	2,756,206	4,445,578	16,091,078	26,223,834	26,223,834	714,862	2,911,476	14,642,533	6,540,697	78,872,415	369,670,687	21,635,909	26,978,700	7,370,399	4,370,237	38,719,336	72,153,852	18,167,371	1,119,142	91,440,364	465,455,569
3.750	3.650	3.600	0.000	40	50,751	1,600,537	2,756,206	4,356,742	16,091,078	26,223,834	26,223,834	708,126	2,884,043	14,504,567	6,545,420	78,929,365	373,339,208	21,703,470	26,977,644	7,384,697	4,370,237	38,732,578	72,151,029	18,202,613	1,119,142	91,472,784	467,843,867
3.800	3.650	3.550	0.000	40	101,503	1,554,299	2,756,206	4,310,505	22,272,462	36,297,712	36,297,712	704,592	2,869,647	14,432,167	6,547,898	78,959,250	376,946,618	21,807,276	26,978,659	7,400,117	4,370,237	38,749,013	72,153,744	18,240,622	1,119,142	91,513,508	487,873,241
3.850	3.650	3.500	0.000	40	101,503	1,482,118	2,756,206	4,238,324	22,272,462	36,297,712	36,297,712	699,033	2,847,009	14,318,315	6,551,795	79,006,246	380,704,061	21,945,423	26,981,759	7,416,664	4,370,237	38,768,659	72,162,033	18,281,409	1,119,142	91,562,583	490,407,224
3.900	3.650	3.450	0.000	40	101,503	1,417,957	2,756,206	4,174,163	22,272,462	36,297,712	36,297,712	694,050	2,826,714	14,216,245	6,555,289	79,048,379	384,508,906	22,116,004	26,986,956	7,434,342	4,370,237	38,791,535	72,175,933	18,324,985	1,119,142	91,620,059	493,013,822
3.950	3.650	3.400	0.000	40	101,503	1,360,550	2,756,206	4,116,756	22,272,462	36,297,712	36,297,712	689,557	2,808,414	14,124,211	6,558,440	79,086,369	388,366,052	22,317,114	26,994,267	7,453,158	4,370,237	38,817,661	72,195,485	18,371,363	1,119,142	91,685,990	495,693,301
4.000	3.650	3.350	0.000	40	101,503	1,308,883	2,756,206	4,065,089	22,272,462	36,297,712	36,297,712	685,484	2,791,828	14,040,796	6,561,295	79,120,801	392,279,911	22,546,848	27,003,707	7,473,115	4,370,237	38,847,059	72,220,732	18,420,556	1,119,142	91,760,430	498,445,953
4.050	3.650	3.300	0.000	40	101,503	1,262,137	2,756,206	4,018,343	22,272,462	36,297,712	36,297,712	681,776	2,776,725	13,964,839	6,563,895	79,152,154	396,254,537	22,803,300	27,015,293	7,494,221	4,370,237	38,879,751	72,251,719	18,472,580	1,119,142	91,843,441	501,272,100
4.100	3.650	3.250	0.000	40	101,503	1,201,438	2,756,206	3,957,644	22,272,462	36,297,712	36,297,712	676,926	2,756,974	13,865,504	6,567,295	79,193,158	400,356,070	23,084,563	27,029,044	7,516,481	4,370,237	38,915,761	72,288,495	18,527,449	1,119,142	91,935,086	504,185,580
4.150	3.650	3.200	0.000	40	101,503	1,163,971	2,756,206	3,920,177	22,272,462	36,297,712	36,297,712	673,913	2,744,702	13,803,786	6,569,408	79,218,634	404,459,741	23,388,733	27,044,978	7,539,902	4,370,237	38,955,116	72,331,111	18,585,179	1,119,142	92,035,431	507,159,354
4.200	3.650	3.150	0.000	40	101,503	1,114,319	2,756,206	3,870,525	22,272,462	36,297,712	36,297,712	669,897	2,728,342	13,721,511	6,572,224	79,252,595	408,689,447	23,713,904	27,063,116	7,564,490	4,370,237	38,997,843	72,379,621	18,645,788	1,119,142	92,144,550	510,220,152
4.250	3.650	3.100	0.000	40	101,503	1,069,760	2,756,206	3,825,966	22,272,462	36,297,712	36,297,712	666,269	2,713,566	13,647,197	6,574,768	79,283,608	412,987,699	24,058,170	27,083,480	7,590,254	4,370,237	39,043,971	72,434,084	18,709,293	1,119,142	92,262,519	513,355,190
4.300	3.650	3.050	0.000	40	101,503	1,029,548	2,756,206	3,785,754	22,272,462	36,297,712	36,297,712	662,975	2,700,152	13,579,737	6,577,078	79,311,117	417,359,001	24,419,626	27,106,093	7,617,201	4,370,237	39,093,531	72,494,562	18,775,716	1,119,142	92,389,420	516,565,187
4.350	3.650	3.000	0.000	40	101,503	981,662	2,756,206	3,737,868	22,272,462	36,297,712	36,297,712	659,029	2,684,080	13,498,904	6,579,844	79,344,483	421,850,010	24,796,365	27,130,980	7,645,340	4,370,237	39,146,558	72,561,122	18,845,076	1,119,142	92,525,340	519,861,247
4.400	3.650	2.950	0.000	40	101,503	949,300	2,756,206	3,705,506	22,272,462	36,297,712	36,297,712	656,347	2,673,156	13,443,964	6,581,725	79,367,162	426,377,405	25,186,483	27,158,168	7,674,680	4,370,237	39,203,085	72,633,836	18,917,396	1,119,142	92,670,373	523,223,063
4.450	3.650	2.900	0.000	40	101,503	910,083	2,756,206	3,666,289	22,272,462	36,297,712	36,297,712	653,079	2,659,850	13,377,044	6,584,016	79,394,785	431,027,206	25,588,073	27,187,685	7,705,231	4,370,237	39,263,153	72,712,779	18,992,700	1,119,142	92,824,620	526,671,669
4.500	3.650	2.850	0.000	40	101,503	883,496	2,756,206	3,639,702	22,272,462	36,297,712	36,297,712	650,854	2,650,786	13,331,461	6,585,576	79,413,601	435,727,876	25,999,231	27,219,562	7,737,002	4,370,237	39,326,801	72,798,033	19,071,014	1,119,142	92,988,188	530,188,976
4.550	3.650	2.800	0.000	40	101,503	850,774	2,756,206	3,606,980	22,272,462	36,297,712	36,297,712	648,103	2,639,582	13,275,114	6,587,505	79,436,860	440,554,542	26,418,049	27,253,832	7,770,006	4,370,237	39,394,075	72,889,686	19,152,365	1,119,142	93,161,193	533,794,261
4.600	3.650	2.750	0.000	40	101,503	821,027	2,756,206	3,577,233	22,272,462	36,297,712	36,297,712	645,591	2,629,350	13,223,654	6,589,267	79,458,101	445,475,109	26,842,624	27,290,529	7,804,254	4,370,237	39,465,020	72,987,832	19,236,784	1,119,142	93,343,758	537,479,397
4.650	3.650	2.700	0.000	40	101,503	793,866	2,756,206	3,550,072	22,272,462	36,297,712	36,297,712	643,287	2,619,968	13,176,470	6,590,882	79,477,578	450,494,109	27,271,048	27,329,693	7,839,760	4,370,237	39,539,689	73,092,574	19,324,302	1,119,142	93,536,018	541,245,674
4.700	3.650	2.650	0.000	40	101,503	762,614	2,756,206	3,518,820	22,272,462	36,297,712	36,297,712	640,625	2,609,126	13,121,940	6,592,748	79,500,087	455,642,327	27,701,417	27,371,363	7,876,537	4,370,237	39,618,137	73,204,020	19,414,954	1,119,142	93,738,116	545,101,821
4.750	3.650	2.600	0.000	40	101,503	740,142	2,756,206	3,496,348	22,272,462	36,297,712	36,297,712	638,703	2,601,298	13,082,572	6,594,096	79,516,337	460,870,282	28,131,825	27,415,585	7,914,600	4,370,237	39,700,421	73,322,289	19,508,777	1,119,142	93,950,208	549,034,320
4.800	3.650	2.550	0.000	40	101,503	713,936	2,756,206	3,470,142	22,272,462	36,297,712	36,297,712	636,453	2,592,135	13,036,492	6,595,673	79,535,359	466,233,630	28,560,366	27,462,405	7,953,966	4,370,237	39,786,608	73,447,509	19,605,811	1,119,142	94,172,462	553,059,139
4.850	3.650	2.500	0.000	40	101,503	690,009	2,756,206	3,446,215	22,272,462	36,297,712	36,297,712	634,391	2,583,737	12,994,256	6,597,119	79,552,792	471,711,211	28,985,134	27,511,876	7,994,653	4,370,237	39,876,766	73,579,818	19,706,100	1,119,142	94,405,060	557,170,714
4.900	3.600	2.500	0.000	40	101,503	668,076	2,718,450	3,386,526	22,272,462	36,297,712	36,297,712	629,214	2,562,652	12,888,211	6,600,749	80,147,405	473,411,176	29,063,333	27,561,367	8,009,498	4,370,237	39,941,101	73,712,179	19,742,691	1,119,142	94,574,012	558,782,511
4.950	3.550	2.500	0.000	40	101,503	647,897	2,680,693	3,328,591	22,272,462	36,297,712	36,297,712	624,143	2,541,996	12,784,330	6,604,305	80,749,398	475,116,220	29,183,486	27,611,464	8,024,459	4,370,237	40,006,160	73,846,164	19,779,569	1,119,142	94,744,875	560,435,261
5.000	3.500	2.500	0.000	40	101,503	629,271	2,642,937	3,272,208	22,272,462	36,297,712	36,297,712	619,162	2,521,710	12,682,306	6,607,797	81,359,058	476,827,147	29,343,386	27,662,177	8,039,538	4,370,237	40,071,952	73,981,795	19,816,738	1,119,142	94,917,674	562,127,860
2.850	3.000	2.575	2.575	50	152,254	3,996,768	2,355,990	6,352,758	26,937,359	43,900,155	43,900,155	1,056,436	2,868,421	17,311,200	8,061,683	37,069,144	210,872,782	33,531,488	24,055,246	6,597,248	4,151,725	34,804,219	64,335,149	16,261,623	1,063,185	81,659,956	365,652,007
2.850	3.050	2.550	2.550	50	152,254	3,996,768	2,395,256	6,392,025	26,937,359	43,900,155	43,900,155	1,059,493	2,876,723	17,361,302	8,059,539	36,781,690	211,622,835	33,614,559	24,060,439	6,616,292	4,151,725	34,828,456	64,349,037	16,308,565	1,063,185	81,720,787	366,138,220
2.850	3.100	2.525	2.525	50	152,254	3,996,768	2,340,887	6,337,656	26,937,359	43,900,155	43,900,155	1,055,257	2,865,221	17,291,887	8,062,509	36,521,676	212,513,439	33,705,862	24,067,501	6,636,150	4,151,725	34,855,376	64,367,924	16,357,513	1,063,185	81,788,622	366,591,618
2.850	3.150	2.500	2.500	50	152,254	3,996,768	2,378,644	6,375,412	26,937,359	43,900,155	43,900,155	1,058,201	2,873,214	17,340,125	8,060,445	36,242,864	213,277,703	33,806,244	24,076,436	6,656,824	4,151,725	34,884,985	64,391,820	16,408,472	1,063,185	81,863,477	367,115,062
2.900	3.000	2.550	2.550	50	152,254	4,066,887	2,355,990	6,422,877	26,937,359	43,900,155	43,900,155	1,061,888	2,883,226	17,400,552	8,057,859	37,051,564	212,147,583	33,852,365	24,073,873	6,620,900	4,151,725	34,846,498	64,384,965	16,319,924	1,063,185	81,768,073	366,921,606
2.900	3.050	2.525	2.525	50	152,254	4,066,887	2,395,256	6,462,143	26,937,359	43,900,155	43,900,155	1,064,928	2,891,480	17,450,363	8,055,728	36,764,298	212,907,781	33,934,021	24,080,334	6,640,612	4,151,725	34,872,671	64,402,245	16,368,512	1,063,185	81,833,942	367,418,187
2.900	3.100	2.500	2.500	50	152,254	4,066,887	2,340,887	6,407,774	26,937,359	43,900,155	43,900,155	1,060,717	2,880,045	17,381,351	8,058,681	36,504,335	213,808,747	34,023,553	24,088,673	6,661,141	4,151,725	34,901,539	64,424,548	16,419,113	1,063,185	81,906,846	367,882,341
2.950	3.000	2.525	2.525	50	152,254	4,137,006	2,355,990	6,492,996	26,937,359	43,900,155	43,900,155	1,067,310	2,897,946	17,489,388	8,054,058	37,034,085	213,439,709	34,171,827	24,093,767	6,645,221	4,151,725	34,890,713	64,438,173	16,379,871	1,063,185	81,881,228	368,206,122
2.950	3.050	2.500	2.500	50	152,254	4,137,006	2,395,256	6,532,262	26,937,359	43,900,155	43,900,155	1,070,332	2,906,152	17,538,913	8,051,939	36,747,006	214,210,248	34,251,711	24,101,506	6,665,604	4,151,725	34,918,834	64,458,869	16,430,113	1,063,185	81,952,166	368,712,992
3.000	3.000	2.500	2.500	50	152,254	4,207,125	2,355,990	6,563,114	26,937,359	43,900,155	43,900,155	1,072,700	2,912,582	17,577,716	8,050,279	37,016,707	214,749,493	34,489,517	24,114,939	6,670,212	4,151,725	34,936,876	64,494,796	16,441,472	1,063,185	81,999,452	369,505,573
3.050	4.300	3.650	0.000	50	101,503	3,992,094	2,164,691	6,156,785	22,272,462	36,297,712	36,297,712	1,041,024	2,826,575	17,058,659	8,072,488	54,695,557	342,635,980	25,189,237	25,487,844	7,009,144	4,370,237	36,867,224	68,166,596	17,276,908	1,119,142	86,562,646	450,717,043
3.100	4.250	3.650	0.000	50	101,503	4,057,538	2,139,521	6,197,059	22,272,462	36,297,712	36,297,712	1,044,212	2,835,232	17,110,902	8,070,253	55,027,587	343,385,486	24,536,466	25,523,117	7,022,185	4,370,237	36,915,539	68,260,933	17,309,054	1,119,142	86,689,129	451,187,502
3.150	4.200	3.650	0.000	50	101,503	4,122,982	2,169,991	6,292,973	22,272,462	36,297,712	36,297,712	1,051,761	2,855,729	17,234,602	8,064,960	55,342,879	344,008,278	23,952,721	25,558,860	7,035,343	4,370,237	36,964,439	68,356,526	17,341,487	1,119,142	86,817,154	451,703,256
3.200	4.150	3.650	0.000	50	101,503	3,926,650	2,144,157	6,070,807	22,272,462	36,297,712	36,297,712	1,034,180	2,807,994	16,946,516	8,077,287	55,783,912	345,387,582	23,435,847	25,595,077	7,048,618	4,370,237	37,013,931	68,453,387	17,374,208	1,119,142	86,946,737	452,316,121
3.250	4.100	3.650	0.000	50	101,503	3,988,004	2,118,324	6,106,328	22,272,462	36,297,712	36,297,712	1,037,014	2,815,687	16,992,948	8,075,300	56,131,162	346,160,165	22,983,687	25,631,774	7,062,010	4,370,237	37,064,021	68,551,531	17,407,220	1,119,142	87,077,893	452,942,395
3.300	4.050	3.650	0.000	50	101,503	4,049,357	2,092,491	6,141,848	22,272,462	36,297,712	36,297,712	1,039,839	2,823,357	17,039,236	8,073,320	56,482,979	346,936,858	22,594,087	25,668,955	7,075,521	4,370,237	37,114,714	68,650,973	17,440,523	1,119,142	87,210,639	453,617,509
3.350	4.000	3.650	0.000	50	101,503	3,868,905	2,122,513	5,991,418	22,272,462	36,297,712	36,297,712	1,027,815	2,790,711	16,842,217	8,081,750	56,912,724	348,165,931	22,264,890	25,706,628	7,089,152	4,370,237	37,166,016	68,751,728	17,474,121	1,119,142	87,344,990	454,371,901
3.400	3.950	3.650	0.000	50	101,503	3,708,502	2,095,982	5,804,484	22,272,462	36,297,712	36,297,712	1,012,649	2,749,531	16,593,691	8,092,384	57,363,765	349,496,337	21,993,941	25,744,797	7,102,902	4,370,237	37,217,936	68,853,811	17,508,013	1,119,142	87,480,965	455,183,381
3.450	3.900	3.650	0.000	50	101,503	3,386,735	2,069,450	5,456,186	22,272,462	36,297,712	36,297,712	983,682	2,670,881	16,119,029	8,112,694	57,889,845	351,252,359	21,779,084	25,783,469	7,116,772	4,370,237	37,270,478	68,957,237	17,542,202	1,119,142	87,618,581	456,081,472
3.500	3.850	3.650	0.000	50	101,503	3,272,208	2,042,919	5,315,127	22,272,462	36,297,712	36,297,712	971,672	2,638,271	15,922,225	8,121,115	58,337,558	352,501,156	21,618,163	25,822,649	7,130,764	4,370,237	37,323,650	69,062,024	17,576,691	1,119,142	87,757,856	456,984,122
3.550	3.800	3.650	0.000	50	101,503	3,030,349	2,016,388	5,046,737	22,272,462	36,297,712	36,297,712	948,344	2,574,931	15,539,958	8,137,472	58,848,690	354,101,571	21,509,024	25,862,344	7,144,877	4,370,237	37,377,459	69,168,187	17,611,480	1,119,142	87,898,809	457,968,255
3.600	3.750	3.650	0.000	50	101,503	2,944,987	1,989,856	4,934,843	22,272,462	36,297,712	36,297,712	938,424	2,547,996	15,377,406	8,144,427	59,298,304	355,299,947	21,449,509	25,902,561	7,159,114	4,370,237	37,431,911	69,275,745	17,646,571	1,119,142	88,041,458	458,955,742
3.650	3.700	3.650	0.000	50	-	2,756,206	1,963,325	4,719,531	-	-	-	918,993	2,495,239	15,059,009	8,158,051	59,802,938	356,796,038	21,437,463	25,943,305	7,173,474	4,370,237	37,487,015	69,384,714	17,681,967	1,119,142	88,185,823	396,706,734
3.700	3.650	3.650	0.000	50	50,751	2,594,393	1,936,793	4,531,187	16,091,078	26,223,834	26,223,834	901,607	2,448,031	14,774,108	8,170,241	60,303,931	358,236,889	21,470,731	25,984,584	7,187,958	4,370,237	37,542,778	69,495,113	17,717,670	1,119,142	88,331,925	443,533,950
3.750	3.650	3.600	0.000	50	50,751	2,454,156	1,936,793	4,390,949	16,091,078	26,223,834	26,223,834	888,410	2,412,201	14,557,867	8,179,494	60,372,224	361,839,643	21,538,292	25,983,528	7,202,256	4,370,237	37,556,021	69,492,290	17,752,912	1,119,142	88,364,345	445,792,629
3.800	3.650	3.550	0.000	50	101,503	2,331,448	1,936,793	4,268,242	22,272,462	36,297,712	36,297,712	876,679	2,380,347	14,365,629	8,187,720	60,432,937	365,461,366	21,642,098	25,984,543	7,217,676	4,370,237	37,572,456	69,495,006	17,790,921	1,119,142	88,405,069	465,707,953
3.850	3.650	3.500	0.000	50	101,503	2,223,177	1,936,793	4,159,970	22,272,462	36,297,712	36,297,712	866,178	2,351,835	14,193,554	8,195,082	60,487,281	369,109,970	21,780,245	25,987,643	7,234,223	4,370,237	37,592,102	69,503,294	17,831,708	1,119,142	88,454,144	468,106,500
3.900	3.650	3.450	0.000	50	101,503	2,069,450	1,936,793	4,006,244	22,272,462	36,297,712	36,297,712	851,016	2,310,667	13,945,102	8,205,713	60,565,747	372,973,957	21,950,826	25,992,840	7,251,901	4,370,237	37,614,978	69,517,195	17,875,284	1,119,142	88,511,620	470,603,506
3.950	3.650	3.400	0.000	50	101,503	1,938,783	1,936,793	3,875,577	22,272,462	36,297,712	36,297,712	837,883	2,275,010	13,729,907	8,214,921	60,633,710	376,844,101	22,151,936	26,000,151	7,270,716	4,370,237	37,641,104	69,536,747	17,921,662	1,119,142	88,577,550	473,167,392
4.000	3.650	3.350	0.000	50	101,503	1,869,833	1,936,793	3,806,627	22,272,462	36,297,712	36,297,712	830,859	2,255,937	13,614,799	8,219,847	60,670,064	380,588,175	22,381,670	26,009,591	7,290,674	4,370,237	37,670,501	69,561,994	17,970,855	1,119,142	88,651,991	475,773,238
4.050	3.650	3.300	0.000	50	101,503	1,807,151	1,936,793	3,743,945	22,272,462	36,297,712	36,297,712	824,414	2,238,438	13,509,191	8,224,365	60,703,417	384,383,775	22,638,122	26,021,177	7,311,780	4,370,237	37,703,193	69,592,981	18,022,879	1,119,142	88,735,002	478,448,833
4.100	3.650	3.250	0.000	50	101,503	1,712,688	1,936,793	3,649,481	22,272,462	36,297,712	36,297,712	814,592	2,211,770	13,348,247	8,231,252	60,754,246	388,363,263	22,919,385	26,034,928	7,334,040	4,370,237	37,739,204	69,629,757	18,077,748	1,119,142	88,826,646	481,218,316
4.150	3.650	3.200	0.000	50	101,503	1,629,560	1,936,793	3,566,353	22,272,462	36,297,712	36,297,712	805,836	2,187,997	13,204,777	8,237,391	60,799,557	392,383,533	23,223,555	26,050,862	7,357,461	4,370,237	37,778,559	69,672,372	18,135,478	1,119,142	88,926,992	484,055,959
4.200	3.650	3.150	0.000	50	101,503	1,555,842	1,936,793	3,492,636	22,272,462	36,297,712	36,297,712	797,981	2,166,668	13,076,055	8,242,899	60,840,210	396,451,379	23,548,726	26,069,000	7,382,049	4,370,237	37,821,286	69,720,882	18,196,087	1,119,142	89,036,111	486,962,226
4.250	3.650	3.100	0.000	50	101,503	1,463,883	1,936,793	3,400,676	22,272,462	36,297,712	36,297,712	788,057	2,139,723	12,913,440	8,249,857	60,891,567	400,669,281	23,892,992	26,089,364	7,407,813	4,370,237	37,867,414	69,775,345	18,259,592	1,119,142	89,154,079	489,957,650
4.300	3.650	3.050	0.000	50	101,503	1,407,049	1,936,793	3,343,843	22,272,462	36,297,712	36,297,712	781,853	2,122,877	12,811,771	8,254,207	60,923,676	404,842,655	24,254,448	26,111,977	7,434,760	4,370,237	37,916,974	69,835,824	18,326,015	1,119,142	89,280,980	493,001,781
4.350	3.650	3.000	0.000	50	101,503	1,334,447	1,936,793	3,271,241	22,272,462	36,297,712	36,297,712	773,845	2,101,134	12,680,548	8,259,822	60,965,119	409,161,989	24,631,187	26,136,864	7,462,899	4,370,237	37,970,000	69,902,384	18,395,375	1,119,142	89,416,901	496,134,115
4.400	3.650	2.950	0.000	50	101,503	1,289,348	1,936,793	3,226,141	22,272,462	36,297,712	36,297,712	768,823	2,087,498	12,598,254	8,263,343	60,991,109	413,463,670	25,021,305	26,164,052	7,492,239	4,370,237	38,026,528	69,975,097	18,467,695	1,119,142	89,561,934	499,318,661

Appendix A

CONFIGURATION: LANE WIDTHS (m)					COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)																											
						Maintenance over design life			Disruption time: Construction roadwork			Disruption time: Maintenance roadwork			Travel time during normal operations				Fuel Consumption				CO2 Emissions				
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2	MPR (%)	Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	WLC - Dual carriagway per km
4.450	3.650	2.900	0.000	50	101,503	1,230,535	1,936,793	3,167,328	22,272,462	36,297,712	36,297,712	762,217	2,069,563	12,490,013	8,267,975	61,025,293	417,909,096	25,422,895	26,193,569	7,522,789	4,370,237	38,086,596	70,054,040	18,542,999	1,119,142	89,716,181	502,591,030
4.500	3.650	2.850	0.000	50	101,503	1,177,995	1,936,793	3,114,788	22,272,462	36,297,712	36,297,712	756,261	2,053,390	12,392,412	8,272,151	61,056,118	422,422,764	25,834,053	26,225,446	7,554,561	4,370,237	38,150,244	70,139,294	18,621,313	1,119,142	89,879,749	505,934,212
4.550	3.650	2.800	0.000	50	101,503	1,130,776	1,936,793	3,067,569	22,272,462	36,297,712	36,297,712	750,862	2,038,732	12,303,946	8,275,936	61,084,057	427,010,124	26,252,871	26,259,716	7,587,565	4,370,237	38,217,517	70,230,947	18,702,664	1,119,142	90,052,753	509,349,171
4.600	3.650	2.750	0.000	50	101,503	1,088,108	1,936,793	3,024,901	22,272,462	36,297,712	36,297,712	745,946	2,025,383	12,223,382	8,279,383	61,109,501	431,676,248	26,677,446	26,296,413	7,621,813	4,370,237	38,288,463	70,329,094	18,787,083	1,119,142	90,235,319	512,836,907
4.650	3.650	2.700	0.000	50	101,503	1,049,363	1,936,793	2,986,157	22,272,462	36,297,712	36,297,712	741,449	2,013,174	12,149,703	8,282,536	61,132,770	436,425,942	27,105,870	26,335,577	7,657,319	4,370,237	38,363,132	70,433,836	18,874,601	1,119,142	90,427,578	516,398,467
4.700	3.650	2.650	0.000	50	101,503	1,003,003	1,936,793	2,939,796	22,272,462	36,297,712	36,297,712	736,028	1,998,455	12,060,870	8,286,337	61,160,825	441,312,115	27,536,239	26,377,247	7,694,095	4,370,237	38,441,579	70,545,282	18,965,253	1,119,142	90,629,676	520,047,540
4.750	3.650	2.600	0.000	50	101,503	971,437	1,936,793	2,908,230	22,272,462	36,297,712	36,297,712	732,311	1,988,362	11,999,959	8,288,943	61,180,062	446,239,985	27,966,647	26,421,469	7,732,159	4,370,237	38,523,864	70,663,551	19,059,076	1,119,142	90,841,768	523,759,680
4.800	3.650	2.550	0.000	50	101,503	933,065	1,936,793	2,869,859	22,272,462	36,297,712	36,297,712	727,764	1,976,014	11,925,441	8,292,132	61,203,596	451,307,635	28,395,188	26,468,289	7,771,525	4,370,237	38,610,051	70,788,771	19,156,110	1,119,142	91,064,022	527,560,727
4.850	3.650	2.500	0.000	50	101,503	898,314	1,936,793	2,835,107	22,272,462	36,297,712	36,297,712	723,617	1,964,756	11,857,495	8,295,039	61,225,055	456,472,200	28,819,956	26,517,760	7,812,212	4,370,237	38,700,208	70,921,080	19,256,399	1,119,142	91,296,620	531,439,629
4.900	3.600	2.500	0.000	50	101,503	866,693	1,910,262	2,776,955	22,272,462	36,297,712	36,297,712	716,618	1,945,751	11,742,799	8,299,947	61,685,230	458,203,059	28,896,382	26,559,580	7,826,821	4,370,237	38,756,638	71,032,927	19,292,410	1,119,142	91,444,478	532,958,164
4.950	3.550	2.500	0.000	50	101,503	830,637	1,883,731	2,714,368	22,272,462	36,297,712	36,297,712	708,997	1,925,060	11,617,923	8,305,290	62,155,078	459,969,151	29,013,810	26,601,949	7,841,557	4,370,237	38,813,743	71,146,242	19,328,732	1,119,142	91,594,115	534,524,615
5.000	3.500	2.500	0.000	50	101,503	811,291	1,857,199	2,668,490	22,272,462	36,297,712	36,297,712	703,351	1,909,731	11,525,412	8,309,249	62,621,084	461,669,668	29,170,085	26,644,874	7,856,419	4,370,237	38,871,530	71,261,043	19,365,366	1,119,142	91,745,551	536,109,027
2.850	3.000	2.575	2.575	60	152,254	3,996,768	1,840,617	5,837,385	26,937,359	43,900,155	43,900,155	1,218,404	2,205,464	16,637,738	9,708,599	28,912,419	209,449,993	33,283,366	23,840,644	6,580,139	4,151,725	34,572,508	63,761,200	16,219,450	1,063,185	81,043,835	358,506,423
2.850	3.050	2.550	2.550	60	152,254	3,996,768	1,871,294	5,868,062	26,937,359	43,900,155	43,900,155	1,221,403	2,210,892	16,678,688	9,706,496	28,689,633	210,180,716	33,376,324	23,850,014	6,599,632	4,151,725	34,601,371	63,786,261	16,267,499	1,063,185	81,116,945	359,026,969
2.850	3.100	2.525	2.525	60	152,254	3,996,768	1,901,971	5,898,739	26,937,359	43,900,155	43,900,155	1,224,394	2,216,305	16,719,524	9,704,400	28,470,177	210,917,003	33,477,114	23,861,204	6,619,946	4,151,725	34,632,875	63,816,189	16,317,571	1,063,185	81,196,944	359,564,932
2.850	3.150	2.500	2.500	60	152,254	3,996,768	1,932,648	5,929,416	26,937,359	43,900,155	43,900,155	1,227,376	2,221,704	16,760,249	9,702,308	28,253,976	211,658,914	33,586,531	23,874,219	6,641,083	4,151,725	34,667,027	63,850,995	16,369,673	1,063,185	81,283,853	360,120,851
2.900	3.000	2.550	2.550	60	152,254	3,795,761	1,840,617	5,636,378	26,937,359	43,900,155	43,900,155	1,198,544	2,169,515	16,366,542	9,722,524	28,953,888	211,104,381	33,604,243	23,859,270	6,603,791	4,151,725	34,614,786	63,811,016	16,277,751	1,063,185	81,151,952	359,608,450
2.900	3.050	2.525	2.525	60	152,254	3,795,761	1,871,294	5,667,055	26,937,359	43,900,155	43,900,155	1,201,599	2,175,045	16,408,259	9,720,382	28,730,675	211,845,152	33,695,786	23,869,909	6,623,952	4,151,725	34,645,586	63,839,470	16,327,446	1,063,185	81,230,100	360,139,708
2.900	3.100	2.500	2.500	60	152,254	3,795,761	1,901,971	5,697,732	26,937,359	43,900,155	43,900,155	1,204,645	2,180,559	16,449,856	9,718,246	28,510,799	212,591,604	33,794,804	23,882,376	6,644,937	4,151,725	34,679,038	63,872,812	16,379,171	1,063,185	81,315,168	360,688,250
2.950	3.000	2.525	2.525	60	152,254	3,861,205	1,840,617	5,701,822	26,937,359	43,900,155	43,900,155	1,205,051	2,181,293	16,455,394	9,717,962	28,940,302	212,376,248	33,923,705	23,879,165	6,628,112	4,151,725	34,659,001	63,864,224	16,337,698	1,063,185	81,265,107	360,877,205
2.950	3.050	2.500	2.500	60	152,254	3,861,205	1,871,294	5,732,499	26,937,359	43,900,155	43,900,155	1,208,087	2,186,789	16,496,857	9,715,833	28,717,229	213,126,911	34,013,476	23,891,081	6,648,943	4,151,725	34,691,749	63,896,093	16,389,047	1,063,185	81,348,324	361,418,452
3.000	3.000	2.500	2.500	60	152,254	3,681,234	1,840,617	5,521,851	26,937,359	43,900,155	43,900,155	1,187,060	2,148,727	16,209,722	9,730,576	28,977,867	214,042,582	34,241,395	23,900,337	6,653,103	4,151,725	34,705,164	63,920,847	16,399,299	1,063,185	81,383,331	362,025,467
3.050	4.300	3.650	0.000	60	101,503	3,522,436	1,688,459	5,210,895	22,272,462	36,297,712	36,297,712	1,155,226	2,091,103	15,775,013	9,752,897	40,593,313	333,872,957	24,937,790	24,748,219	6,844,052	4,370,237	35,962,508	66,188,488	16,869,971	1,119,142	84,177,601	432,332,460
3.100	4.250	3.650	0.000	60	101,503	3,580,181	1,668,826	5,249,007	22,272,462	36,297,712	36,297,712	1,159,181	2,098,262	15,829,020	9,750,124	40,839,432	334,642,351	24,300,163	24,776,757	6,856,560	4,370,237	36,003,554	66,264,812	16,900,803	1,119,142	84,284,756	432,750,158
3.150	4.200	3.650	0.000	60	101,503	3,435,818	1,649,193	5,085,011	22,272,462	36,297,712	36,297,712	1,142,052	2,067,257	15,595,122	9,762,134	41,151,011	335,924,433	23,729,961	24,805,734	6,869,197	4,370,237	36,045,167	66,342,308	16,931,952	1,119,142	84,393,402	433,243,293
3.200	4.150	3.650	0.000	60	101,503	3,490,355	1,662,816	5,153,171	22,272,462	36,297,712	36,297,712	1,149,206	2,080,207	15,692,814	9,757,117	41,394,366	336,625,785	23,225,078	24,835,153	6,881,964	4,370,237	36,087,353	66,420,989	16,963,421	1,119,142	84,503,552	433,758,692
3.250	4.100	3.650	0.000	60	101,503	3,358,319	1,642,782	5,001,101	22,272,462	36,297,712	36,297,712	1,133,174	2,051,187	15,473,894	9,768,358	41,710,287	337,893,132	22,783,408	24,865,019	6,894,861	4,370,237	36,130,116	66,500,866	16,995,211	1,119,142	84,615,218	434,352,843
3.300	4.050	3.650	0.000	60	101,503	3,239,486	1,691,801	4,931,287	22,272,462	36,297,712	36,297,712	1,125,728	2,037,708	15,372,207	9,773,579	42,004,454	338,958,349	22,402,847	24,895,337	6,907,888	4,370,237	36,173,461	66,581,949	17,027,322	1,119,142	84,728,413	434,984,948
3.350	4.000	3.650	0.000	60	101,503	3,288,569	1,707,239	4,995,808	22,272,462	36,297,712	36,297,712	1,132,612	2,050,169	15,466,212	9,768,753	42,259,011	339,679,765	22,081,287	24,926,110	6,921,047	4,370,237	36,217,394	66,664,253	17,059,757	1,119,142	84,843,152	435,642,367
3.400	3.950	3.650	0.000	60	101,503	3,178,716	1,723,363	4,902,079	22,272,462	36,297,712	36,297,712	1,122,596	2,032,038	15,329,438	9,775,775	42,568,528	340,818,095	21,816,624	24,957,344	6,934,337	4,370,237	36,261,919	66,747,788	17,092,518	1,119,142	84,959,447	436,370,619
3.450	3.900	3.650	0.000	60	101,503	3,078,850	1,740,220	4,819,070	22,272,462	36,297,712	36,297,712	1,113,640	2,015,827	15,207,142	9,782,055	42,878,900	341,936,443	21,606,752	24,989,044	6,947,761	4,370,237	36,307,041	66,832,567	17,125,605	1,119,142	85,077,314	437,142,382
3.500	3.850	3.650	0.000	60	101,503	3,123,471	1,757,861	4,881,332	22,272,462	36,297,712	36,297,712	1,120,365	2,028,000	15,298,975	9,777,340	43,144,907	342,675,365	21,449,565	25,021,214	6,961,317	4,370,237	36,352,768	66,918,604	17,159,021	1,119,142	85,196,767	437,929,848
3.550	3.800	3.650	0.000	60	101,503	3,030,349	1,735,031	4,765,380	22,272,462	36,297,712	36,297,712	1,107,803	2,005,263	15,127,446	9,786,147	43,474,570	343,893,402	21,342,957	25,053,858	6,975,008	4,370,237	36,399,103	67,005,912	17,192,767	1,119,142	85,317,821	438,792,854
3.600	3.750	3.650	0.000	60	101,503	3,073,030	1,752,969	4,825,999	22,272,462	36,297,712	36,297,712	1,114,390	2,017,186	15,217,393	9,781,529	43,748,655	344,644,866	21,284,823	25,086,984	6,988,833	4,370,237	36,446,054	67,094,505	17,226,845	1,119,142	85,440,491	439,660,517
3.650	3.700	3.650	0.000	60	-	2,985,890	1,729,596	4,715,485	-	-	-	1,102,348	1,995,388	15,052,954	9,789,972	44,085,301	345,861,785	21,273,057	25,120,595	7,002,794	4,370,237	36,493,625	67,184,396	17,261,256	1,119,142	85,564,794	377,289,807
3.700	3.650	3.650	0.000	60	50,751	2,793,962	1,747,838	4,541,800	16,091,078	26,223,834	26,223,834	1,083,116	1,960,575	14,790,328	9,803,457	44,449,433	347,263,795	21,305,553	25,154,697	7,016,890	4,370,237	36,541,824	67,275,601	17,296,003	1,119,142	85,690,746	424,013,416
3.750	3.650	3.600	0.000	60	50,751	2,726,840	1,747,838	4,474,678	16,091,078	26,223,834	26,223,834	1,075,579	1,946,932	14,687,407	9,808,741	44,473,394	350,452,845	21,373,114	25,153,168	7,031,188	4,370,237	36,555,066	67,272,779	17,331,246	1,119,142	85,723,167	426,106,947
3.800	3.650	3.550	0.000	60	101,503	2,572,632	1,747,838	4,320,470	22,272,462	36,297,712	36,297,712	1,058,033	1,915,171	14,447,806	9,821,044	44,529,174	353,950,411	21,476,920	25,154,656	7,046,608	4,370,237	36,571,501	67,275,494	17,369,255	1,119,142	85,763,891	445,882,540
3.850	3.650	3.500	0.000	60	101,503	2,438,323	1,747,838	4,186,161	22,272,462	36,297,712	36,297,712	1,042,477	1,887,014	14,235,395	9,831,951	44,578,625	357,458,718	21,615,067	25,157,756	7,063,155	4,370,237	36,591,147	67,283,782	17,410,042	1,119,142	85,812,966	448,139,273
3.900	3.650	3.450	0.000	60	101,503	2,320,293	1,747,838	4,068,131	22,272,462	36,297,712	36,297,712	1,028,587	1,861,872	14,045,722	9,841,690	44,622,783	360,986,434	21,785,648	25,162,953	7,080,834	4,370,237	36,614,023	67,297,683	17,453,617	1,119,142	85,870,442	450,463,147
3.950	3.650	3.400	0.000	60	101,503	2,154,204	1,747,838	3,902,042	22,272,462	36,297,712	36,297,712	1,008,674	1,825,826	13,773,799	9,855,652	44,686,088	364,733,581	21,986,758	25,170,264	7,099,649	4,370,237	36,640,149	67,317,235	17,499,995	1,119,142	85,936,372	452,878,887
4.000	3.650	3.350	0.000	60	101,503	2,066,658	1,747,838	3,814,496	22,272,462	36,297,712	36,297,712	997,996	1,806,498	13,627,992	9,863,139	44,720,033	368,306,590	22,216,492	25,179,704	7,119,606	4,370,237	36,669,547	67,342,482	17,549,189	1,119,142	86,010,813	455,335,323
4.050	3.650	3.300	0.000	60	101,503	1,987,866	1,747,838	3,735,704	22,272,462	36,297,712	36,297,712	988,275	1,788,901	13,495,238	9,869,955	44,750,939	371,919,456	22,472,944	25,191,290	7,140,712	4,370,237	36,702,239	67,373,469	17,601,213	1,119,142	86,093,824	457,857,909
4.100	3.650	3.250	0.000	60	101,503	1,872,007	1,747,838	3,619,845	22,272,462	36,297,712	36,297,712	973,779	1,762,662	13,297,300	9,880,118	44,797,021	375,726,050	22,754,207	25,205,041	7,162,972	4,370,237	36,738,249	67,410,245	17,656,082	1,119,142	86,185,468	460,469,393
4.150	3.650	3.200	0.000	60	101,503	1,771,260	1,747,838	3,519,098	22,272,462	36,297,712	36,297,712	960,973	1,739,482	13,122,428	9,889,097	44,837,732	379,557,847	23,058,377	25,220,975	7,186,393	4,370,237	36,777,604	67,452,860	17,713,812	1,119,142	86,285,814	463,145,228
4.200	3.650	3.150	0.000	60	101,503	1,682,850	1,747,838	3,430,688	22,272,462	36,297,712	36,297,712	949,574	1,718,847	12,966,765	9,897,090	44,873,972	383,423,224	23,383,548	25,239,113	7,210,982	4,370,237	36,820,331	67,501,370	17,774,420	1,119,142	86,394,933	465,885,574
4.250	3.650	3.100	0.000	60	101,503	1,604,640	1,747,838	3,352,478	22,272,462	36,297,712	36,297,712	939,359	1,700,357	12,827,278	9,904,252	44,906,445	387,329,227	23,727,814	25,259,477	7,236,745	4,370,237	36,866,459	67,555,833	17,837,926	1,119,142	86,512,901	468,690,641
4.300	3.650	3.050	0.000	60	101,503	1,534,963	1,747,838	3,282,801	22,272,462	36,297,712	36,297,712	930,151	1,683,690	12,701,545	9,910,708	44,935,717	391,281,930	24,089,270	25,282,090	7,263,693	4,370,237	36,916,019	67,616,312	17,904,349	1,119,142	86,639,802	471,560,682
4.350	3.650	3.000	0.000	60	101,503	1,472,494	1,747,838	3,220,332	22,272,462	36,297,712	36,297,712	921,808	1,668,587	12,587,609	9,916,558	44,962,242	395,286,688	24,466,009	25,306,977	7,291,832	4,370,237	36,969,046	67,682,872	17,973,709	1,119,142	86,775,722	474,495,993
4.400	3.650	2.950	0.000	60	101,503	1,416,169	1,747,838	3,164,007	22,272,462	36,297,712	36,297,712	914,211	1,654,836	12,483,869	9,921,885	44,986,394	399,348,328	24,856,127	25,334,165	7,321,171	4,370,237	37,025,573	67,755,586	18,046,029	1,119,142	86,920,756	477,496,916
4.450	3.650	2.900	0.000	60	101,503	1,344,122	1,747,838	3,091,960	22,272,462	36,297,712	36,297,712	904,388	1,637,055	12,349,733	9,928,773	45,017,622	403,553,243	25,257,717	25,363,682	7,351,722	4,370,237	37,085,641	67,834,528	18,121,333	1,119,142	87,075,003	480,580,348
4.500	3.650	2.850	0.000	60	101,503	1,299,259	1,747,838	3,047,097	22,272,462	36,297,712	36,297,712	898,209	1,625,871	12,265,366	9,933,104	45,037,263	407,736,736	25,668,875	25,395,559	7,383,493	4,370,237	37,149,289	67,919,782	18,199,647	1,119,142	87,238,571	483,713,181
4.550	3.650	2.800	0.000	60	101,503	1,240,712	1,747,838	2,988,550	22,272,462	36,297,712	36,297,712	890,074	1,611,145	12,154,269	9,938,809	45,063,127	412,061,017	26,087,693	25,429,829	7,416,497	4,370,237	37,216,563	68,011,436	18,280,998	1,119,142	87,411,575	486,928,141
4.600	3.650	2.750	0.000	60	101,503	1,204,173	1,747,838	2,952,010	22,272,462	36,297,712	36,297,712	884,953	1,601,876	12,084,346	9,942,399	45,079,406	416,384,344	26,512,268	25,466,526	7,450,745	4,370,237	37,287,509	68,109,582	18,365,417	1,119,142	87,594,141	490,195,093
4.650	3.650	2.700	0.000	60	101,503	1,155,628	1,747,838	2,903,466	22,272,462	36,297,712	36,297,712	878,098	1,589,467	11,990,735	9,947,206	45,101,199	420,847,590	26,940,692	25,505,690	7,486,251	4,370,237	37,362,178	68,214,324	18,452,935	1,119,142	87,786,400	493,544,279
4.700	3.650	2.650	0.000	60	101,503	1,111,762	1,747,838	2,859,600	22,272,462	36,297,712	36,297,712	871,851	1,578,159	11,905,429	9,951,586	45,121,059	425,384,875	27,371,061	25,547,360	7,523,028	4,370,237	37,440,625	68,325,770	18,543,587	1,119,142	87,988,498	496,961,421
4.750	3.650	2.600	0.000	60	101,503	1,059,749	1,747,838	2,807,587	22,272,462	36,297,712	36,297,712	864,377	1,564,631	11,803,373	9,956,826	45,144,818	430,054,086	27,801,469	25,591,582	7,561,091	4,370,237	37,522,910	68,444,039	18,637,409	1,119,142	88,200,590	500,460,037
4.800	3.650	2.550	0.000	60	101,503	1,024,343	1,747,838	2,772,181	22,272,462	36,297,712	36,297,712	859,248	1,555,346	11,733,328	9,960,423	45,161,125	434,750,121	28,230,010	25,638,402	7,600,457	4,370,237	37,609,096	68,569,259	18,734,443	1,119,142	88,422,844	504,015,406
4.850	3.650	2.500	0.000	60	101,503	991,888	1,747,838	2,739,726	22,272,462	36,297,712	36,297,712	854,515	1,546,779	11,668,701	9,963,741	45,176,171	439,534,069	28,654,778	25,687,873	7,641,144	4,370,237	37,699,254	68,701,568	18,834,732	1,119,142	88,655,442	507,641,709
4.900	3.600	2.500	0.000	60	101,503	952,504	1,812,300	2,764,804	22,272,462	36,297,712	36,297,712	858,174	1,553,403	11,718,673	9,961,175	45,477,093	440,888,273	28,729,431	25,722,471	7,655,378	4,370,237	37,748,086	68,794,101	18,869,817	1,119,142	88,783,060	508,967,707
4.950	3.550	2.500	0.000	60	101,503	925,567	1,787,129	2,712,696	22,272,462	36,297,712	36,297,712	850,551	1,539,603	11,614,567	9,966,521	45,818,580	442,602,888	28,844,135	25,757,572	7,669,749	4,370,237	37,797,558	68,887,977	18,905,241	1,119,142	88,912,360	510,419,231
5.000	3.500	2.500	0.000	60	101,503	892,420	1,808,325	2,700,746	22,272,462	36,297,712	36,297,712	848,791	1,536,418	11,590,541	9,967,754	46,145,823	444,145,814	28,996,784	25,793,182	7,684,259	4,370,237	37,847,677	68,983,213	18,941,007	1,119,142	89,043,362	511,862,066
2.850	3.000	2.575	2.575	70	152,254	3,996,768	1,549,993	5,546,762	26,937,359	43,900,155	43,900,155	1,387,830	1,614,951	16,243,978	11,350,287	21,220,215	208,085,540	33,035,244	23,654,129	6,567,443	4,151,725	34,373,296	63,262,370	16,188,156	1,063,185	80,513,710	352,174,491
2.850	3.050	2.550	2.550	70	152,254	3,996,768	1,535,421	5,532,189	26,937,359	43,900,155	43,900,155	1,386,119	1,612,960	16,223,948	11,351,486	21,063,489	208,858,601	33,138,089	23,667,085	6,587,335	4,151,725	34,406,145	63,297,021	16,237,188	1,063,185	80,597,395	352,706,896
2.850	3.100	2.525	2.525	70	152,254	3,996,768	1,521,577	5,518,345	26,937,359	43,900,155	43,900,155	1,384,491	1,611,065	16,204,895	11,352,628	20,908,987	209,636,183	33,248,365	23,681,807	6,608,055	4,151,725	34,441,587	63,336,396	16,288,261	1,063,185	80,687,842	353,256,207
2.850	3.150	2.500	2.500	70	152,254	3,996,768	1,546,118	5,542,887	26,937,359	43,900,155	43,900,155	1,387,375	1,614,422	16,238,654	11,350,606	20,750,980	210,360,784	33,366,817	23,698,301	6,629,605	4,151,725	34,479,631	63,380,509	16,341,379	1,063,185	80,785,073	353,844,768
2.900	3.000	2.550	2.550	70	152,254	4,066,887	1,549,993	5,616,880	26,937,359	43,900,155	43,900,155	1,396,031	1,624,494	16,339,964	11,344,537	21,209,465	209,311,083	33,356,121	23,672,755	6,591,095	4,151,725	34,415,575	63,312,186	16,246,456	1,063,185	80,621,827	353,417,266
2.900	3.050	2.525	2.525	70	152,254	4,066,887	1,535,421	5,602,308	26,937,359	43,900,155	43,900,155	1,394,331	1,622,516	16,320,068	11,345,729	21,052,805	210,093,412	33,457,551	23,686,980	6,611,655	4,151,725	34,450,360	63,350,230	16,297,136	1,063,185	80,710,550	353,959,702
2.900	3.100	2.500	2.500	70	152,254	4,066,887	1,521,577	5,588,464	26,937,359	43,900,155	43,900,155	1,392,714	1,620,634	16,301,141	11,346,862	20,898,368	210,880,366	33,566,055	23,702,979	6,633,046	4,151,725	34,487,750	63,393,020	16,349,862	1,063,185	80,806,066	354,518,896
2.950	3.000	2.525	2.525	70	152,254	4,137,006	1,549,993	5,686,999	26,937,359	43,900,155	43,900,155	1,404,177	1,633,973	16,435,316	11,338,825	21,198,786	210,553,117	33,675,583	23,692,650	6,615,415	4,151,725	34,459,790	63,365,394	16,306,404	1,063,185	80,734,982	354,674,315
2.950	3.050	2.500	2.500	70	152,254	4,137,006	1,535,421	5,672,427	26,937,359	43,900,155	43,900,155	1,402,489	1,632,008	16,415,551	11,340,009	21,042,192	211,344,898	33,775,242	23,708,152	6,636,647	4,151,725	34,496,523	63,406,853	16,358,736	1,063,185	80,828,774	355,226,690
3.000	3.000	2.500	2.500	70	152,254	3,926,650	1,549,993	5,476,643	26,937,359	43,900,155	43,900,155	1,379,574	1,605,344	16,147,345	11,356,075	21,231,038	212,240,417	33,993,273	23,713,822	6,640,407	4,151,725	34,505,953	63,422,017	16,368,004	1,063,185	80,853,206	355,785,861

CONFIGURATION: LANE WIDTHS (m)				MPR	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)																		CO2 Emissions				WLC - Dual carriageway per km
						Maintenance over design life			Disruption time: Construction roadworks			Disruption time: Maintenance roadworks			Travel time during normal operations				Fuel Consumption								
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2	(%)	Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	
3.050	4.300	3.650	0.000	70	101,503	3,992,094	1,241,514	5,233,608	22,272,462	36,297,712	36,297,712	1,350,515	1,571,530	15,807,224	11,376,450	28,166,199	323,137,969	24,686,342	24,152,956	6,695,163	4,370,237	35,218,356	64,596,471	16,502,975	1,119,142	82,218,587	415,824,113
3.100	4.250	3.650	0.000	70	101,503	4,057,538	1,227,078	5,284,616	22,272,462	36,297,712	36,297,712	1,356,673	1,578,694	15,879,293	11,372,133	28,334,275	323,890,504	24,063,860	24,175,027	6,706,953	4,370,237	35,252,217	64,655,500	16,532,035	1,119,142	82,306,677	416,192,220
3.150	4.200	3.650	0.000	70	101,503	3,865,296	1,212,642	5,077,937	22,272,462	36,297,712	36,297,712	1,331,524	1,549,431	15,584,943	11,389,766	28,559,538	325,273,985	23,507,201	24,197,514	6,718,886	4,370,237	35,286,636	64,715,641	16,561,449	1,119,142	82,396,231	416,617,721
3.200	4.150	3.650	0.000	70	101,503	3,926,650	1,198,206	5,124,855	22,272,462	36,297,712	36,297,712	1,337,280	1,556,129	15,652,313	11,385,730	28,733,015	326,044,500	23,014,309	24,220,419	6,730,962	4,370,237	35,321,618	64,776,900	16,591,217	1,119,142	82,487,258	417,084,264
3.250	4.100	3.650	0.000	70	101,503	3,753,415	1,201,438	4,954,853	22,272,462	36,297,712	36,297,712	1,316,289	1,531,702	15,406,617	11,400,448	28,956,372	327,357,734	22,583,130	24,243,746	6,743,184	4,370,237	35,357,167	64,839,288	16,621,341	1,119,142	82,579,770	417,608,979
3.300	4.050	3.650	0.000	70	101,503	3,811,160	1,186,786	4,997,946	22,272,462	36,297,712	36,297,712	1,321,646	1,537,935	15,469,315	11,396,692	29,135,410	328,146,233	22,211,607	24,267,499	6,755,550	4,370,237	35,393,285	64,902,813	16,651,822	1,119,142	82,673,777	418,168,823
3.350	4.000	3.650	0.000	70	101,503	3,868,905	1,189,894	5,058,799	22,272,462	36,297,712	36,297,712	1,329,168	1,546,689	15,557,366	11,391,417	29,312,888	328,895,216	21,897,685	24,291,680	6,768,061	4,370,237	35,429,978	64,967,486	16,682,662	1,119,142	82,769,289	418,771,923
3.400	3.950	3.650	0.000	70	101,503	3,708,502	1,175,020	4,883,523	22,272,462	36,297,712	36,297,712	1,307,367	1,521,320	15,302,195	11,406,703	29,545,966	330,243,584	21,639,308	24,316,294	6,780,719	4,370,237	35,467,250	65,033,315	16,713,862	1,119,142	82,866,319	419,435,282
3.450	3.900	3.650	0.000	70	101,503	3,763,039	1,160,146	4,923,186	22,272,462	36,297,712	36,297,712	1,312,337	1,527,103	15,360,358	11,403,219	29,733,199	331,054,475	21,434,420	24,341,344	6,793,524	4,370,237	35,505,104	65,100,311	16,745,424	1,119,142	82,964,877	420,125,110
3.500	3.850	3.650	0.000	70	101,503	3,817,576	1,162,892	4,980,468	22,272,462	36,297,712	36,297,712	1,319,476	1,535,411	15,443,921	11,398,213	29,918,942	331,825,561	21,280,967	24,366,834	6,806,475	4,370,237	35,543,547	65,168,484	16,777,349	1,119,142	83,064,975	420,853,912
3.550	3.800	3.650	0.000	70	101,503	3,668,317	1,147,790	4,816,107	22,272,462	36,297,712	36,297,712	1,298,872	1,511,434	15,202,757	11,412,660	30,158,592	333,168,804	21,176,891	24,392,769	6,819,575	4,370,237	35,582,581	65,237,844	16,809,639	1,119,142	83,166,625	421,643,141
3.600	3.750	3.650	0.000	70	101,503	3,719,984	1,132,687	4,852,671	22,272,462	36,297,712	36,297,712	1,303,487	1,516,805	15,256,780	11,409,424	30,354,447	334,001,876	21,120,137	24,419,151	6,832,824	4,370,237	35,622,212	65,308,403	16,842,295	1,119,142	83,269,840	422,451,379
3.650	3.700	3.650	0.000	70	-	3,583,068	1,135,047	4,718,115	-	-	-	1,286,409	1,496,933	15,056,890	11,421,398	30,593,718	335,286,116	21,108,651	24,445,986	6,846,222	4,370,237	35,662,444	65,380,172	16,875,320	1,119,142	83,374,633	360,003,538
3.700	3.650	3.650	0.000	70	50,751	3,459,191	1,137,482	4,596,673	16,091,078	26,223,834	26,223,834	1,270,773	1,478,737	14,873,868	11,432,362	30,833,553	336,547,805	21,140,375	24,473,277	6,859,769	4,370,237	35,703,283	65,453,161	16,908,714	1,119,142	83,481,017	406,631,962
3.750	3.650	3.600	0.000	70	50,751	3,346,576	1,137,482	4,484,058	16,091,078	26,223,834	26,223,834	1,256,075	1,461,634	14,701,839	11,442,667	30,861,346	339,672,136	21,207,936	24,472,221	6,874,067	4,370,237	35,716,525	65,450,338	16,943,957	1,119,142	83,513,437	408,604,768
3.800	3.650	3.550	0.000	70	101,503	3,243,754	1,137,482	4,381,236	22,272,462	36,297,712	36,297,712	1,242,483	1,445,818	14,542,755	11,452,197	30,887,049	342,826,027	21,311,742	24,473,237	6,889,487	4,370,237	35,732,960	65,453,054	16,981,966	1,119,142	83,554,161	428,230,544
3.850	3.650	3.500	0.000	70	101,503	3,023,520	1,137,482	4,161,002	22,272,462	36,297,712	36,297,712	1,212,790	1,411,265	14,195,205	11,473,017	30,943,200	346,374,486	21,449,889	24,476,336	6,906,034	4,370,237	35,752,606	65,461,342	17,022,752	1,119,142	83,603,236	430,364,056
3.900	3.650	3.450	0.000	70	101,503	2,944,987	1,137,482	4,082,469	22,272,462	36,297,712	36,297,712	1,202,000	1,398,710	14,068,918	11,480,582	30,963,604	349,580,314	21,620,470	24,481,533	6,923,712	4,370,237	35,775,482	65,475,243	17,066,328	1,119,142	83,660,712	432,535,100
3.950	3.650	3.400	0.000	70	101,503	2,769,690	1,137,482	3,907,172	22,272,462	36,297,712	36,297,712	1,177,512	1,370,214	13,782,290	11,497,752	31,009,912	353,136,702	21,821,580	24,488,844	6,942,528	4,370,237	35,801,608	65,494,795	17,112,706	1,119,142	83,726,643	434,800,516
4.000	3.650	3.350	0.000	70	101,503	2,617,766	1,137,482	3,755,248	22,272,462	36,297,712	36,297,712	1,155,812	1,344,963	13,528,305	11,512,967	31,050,947	356,694,677	22,051,314	24,498,284	6,962,485	4,370,237	35,831,006	65,520,042	17,161,900	1,119,142	83,801,083	437,130,474
4.050	3.650	3.300	0.000	70	101,503	2,484,833	1,137,482	3,622,315	22,272,462	36,297,712	36,297,712	1,136,439	1,322,420	13,301,554	11,526,550	31,087,582	360,264,407	22,307,766	24,509,870	6,983,591	4,370,237	35,863,698	65,551,029	17,213,923	1,119,142	83,884,094	439,524,142
4.100	3.650	3.250	0.000	70	101,503	2,367,539	1,137,482	3,505,021	22,272,462	36,297,712	36,297,712	1,119,030	1,302,161	13,097,781	11,538,757	31,120,504	363,854,243	22,589,029	24,523,621	7,005,851	4,370,237	35,899,708	65,587,805	17,268,792	1,119,142	83,975,739	441,980,908
4.150	3.650	3.200	0.000	70	101,503	2,263,277	1,137,482	3,400,759	22,272,462	36,297,712	36,297,712	1,103,293	1,283,849	12,913,588	11,549,791	31,150,263	367,471,206	22,893,199	24,539,555	7,029,272	4,370,237	35,939,063	65,630,420	17,326,522	1,119,142	84,076,084	444,500,323
4.200	3.650	3.150	0.000	70	101,503	2,169,991	1,137,482	3,307,472	22,272,462	36,297,712	36,297,712	1,088,994	1,267,210	12,746,225	11,559,816	31,177,303	371,121,321	23,218,370	24,557,693	7,053,860	4,370,237	35,981,790	65,678,930	17,387,131	1,119,142	84,185,203	447,082,062
4.250	3.650	3.100	0.000	70	101,503	2,086,033	1,137,482	3,223,514	22,272,462	36,297,712	36,297,712	1,075,941	1,252,020	12,593,442	11,568,969	31,201,987	374,809,863	23,562,636	24,578,057	7,079,624	4,370,237	36,027,918	65,733,393	17,450,637	1,119,142	84,303,172	449,725,901
4.300	3.650	3.050	0.000	70	101,503	1,963,325	1,137,482	3,100,807	22,272,462	36,297,712	36,297,712	1,056,534	1,229,437	12,366,292	11,582,576	31,238,686	378,712,113	23,924,092	24,600,670	7,106,572	4,370,237	36,077,479	65,793,872	17,517,059	1,119,142	84,430,073	452,458,318
4.350	3.650	3.000	0.000	70	101,503	1,897,881	1,137,482	3,035,362	22,272,462	36,297,712	36,297,712	1,046,016	1,217,199	12,243,191	11,589,950	31,258,575	382,481,330	24,300,831	24,625,557	7,134,711	4,370,237	36,130,505	65,860,432	17,586,419	1,119,142	84,565,993	455,225,561
4.400	3.650	2.950	0.000	70	101,503	1,799,714	1,137,482	2,937,196	22,272,462	36,297,712	36,297,712	1,030,012	1,198,575	12,055,866	11,601,172	31,288,840	386,449,546	24,690,949	24,652,745	7,164,050	4,370,237	36,187,032	65,933,145	17,658,739	1,119,142	84,711,026	458,079,736
4.450	3.650	2.900	0.000	70	101,503	1,747,359	1,137,482	2,884,841	22,272,462	36,297,712	36,297,712	1,021,360	1,188,508	11,954,599	11,607,238	31,305,201	390,319,698	25,092,539	24,682,263	7,194,601	4,370,237	36,247,100	66,012,088	17,734,043	1,119,142	84,865,273	460,970,498
4.500	3.650	2.850	0.000	70	101,503	1,666,974	1,137,482	2,804,456	22,272,462	36,297,712	36,297,712	1,007,912	1,172,859	11,797,197	11,616,667	31,330,632	394,378,145	25,503,697	24,714,139	7,226,372	4,370,237	36,310,749	66,097,342	17,812,357	1,119,142	85,028,841	463,947,029
4.550	3.650	2.800	0.000	70	101,503	1,595,201	1,137,482	2,732,683	22,272,462	36,297,712	36,297,712	995,731	1,158,684	11,654,623	11,625,208	31,353,666	398,484,639	25,922,515	24,748,409	7,259,376	4,370,237	36,378,022	66,188,995	17,893,709	1,119,142	85,201,846	466,984,671
4.600	3.650	2.750	0.000	70	101,503	1,530,728	1,137,482	2,668,210	22,272,462	36,297,712	36,297,712	984,643	1,145,782	11,524,843	11,632,982	31,374,634	402,644,802	26,347,090	24,785,107	7,293,624	4,370,237	36,448,968	66,287,142	17,978,128	1,119,142	85,384,411	470,083,836
4.650	3.650	2.700	0.000	70	101,503	1,472,494	1,137,482	2,609,975	22,272,462	36,297,712	36,297,712	974,505	1,133,985	11,406,183	11,640,090	31,393,805	406,863,727	26,775,514	24,824,270	7,329,130	4,370,237	36,523,637	66,391,884	18,065,645	1,119,142	85,576,671	473,244,988
4.700	3.650	2.650	0.000	70	101,503	1,419,635	1,137,482	2,557,117	22,272,462	36,297,712	36,297,712	965,199	1,123,155	11,297,253	11,646,616	31,411,404	411,146,110	27,205,883	24,865,940	7,365,907	4,370,237	36,602,084	66,503,330	18,156,297	1,119,142	85,778,769	476,468,652
4.750	3.650	2.600	0.000	70	101,503	1,371,440	1,137,482	2,508,922	22,272,462	36,297,712	36,297,712	956,624	1,113,177	11,196,888	11,652,628	31,427,620	415,496,355	27,636,291	24,910,162	7,403,970	4,370,237	36,684,369	66,621,599	18,250,120	1,119,142	85,990,861	479,755,415
4.800	3.650	2.550	0.000	70	101,503	1,308,883	1,137,482	2,446,365	22,272,462	36,297,712	36,297,712	945,362	1,100,072	11,065,074	11,660,524	31,448,916	420,002,867	28,064,832	24,956,982	7,443,336	4,370,237	36,770,555	66,746,819	18,347,154	1,119,142	86,213,115	483,124,714
4.850	3.650	2.500	0.000	70	101,503	1,269,617	1,137,482	2,407,099	22,272,462	36,297,712	36,297,712	938,215	1,091,756	10,981,419	11,665,536	31,462,432	424,496,926	28,489,600	25,006,453	7,484,023	4,370,237	36,860,713	66,879,128	18,447,443	1,119,142	86,445,712	486,539,197
4.900	3.600	2.500	0.000	70	101,503	1,217,758	1,158,683	2,376,442	22,272,462	36,297,712	36,297,712	932,592	1,085,212	10,915,603	11,669,478	31,690,871	426,115,445	28,562,480	25,034,205	7,497,722	4,370,237	36,902,163	66,953,350	18,481,209	1,119,142	86,553,700	487,848,917
4.950	3.550	2.500	0.000	70	101,503	1,185,178	1,161,634	2,346,812	22,272,462	36,297,712	36,297,712	927,120	1,078,845	10,851,559	11,673,315	31,922,204	427,741,354	28,674,459	25,062,423	7,511,572	4,370,237	36,944,231	67,028,817	18,515,348	1,119,142	86,663,306	489,195,062
5.000	3.500	2.500	0.000	70	101,503	1,141,468	1,184,765	2,326,233	22,272,462	36,297,712	36,297,712	923,298	1,074,398	10,806,827	11,675,994	32,153,598	429,336,100	28,823,483	25,091,110	7,525,574	4,370,237	36,986,921	67,105,541	18,549,862	1,119,142	86,774,545	490,567,190
2.850	3.000	2.575	2.575	80	152,254	4,304,212	879,101	5,183,313	26,937,359	43,900,155	43,900,155	1,536,472	1,042,952	15,735,797	13,006,547	13,917,871	207,189,295	32,787,122	23,486,707	6,558,202	4,151,725	34,196,634	62,814,606	16,165,377	1,063,185	80,043,168	346,352,728
2.850	3.050	2.550	2.550	80	152,254	4,304,212	880,609	5,184,821	26,937,359	43,900,155	43,900,155	1,536,681	1,043,095	15,737,944	13,006,400	13,813,462	207,918,486	32,899,854	23,502,726	6,578,436	4,151,725	34,232,887	62,857,447	16,215,253	1,063,185	80,135,884	346,932,958
2.850	3.100	2.525	2.525	80	152,254	4,304,212	882,073	5,186,286	26,937,359	43,900,155	43,900,155	1,536,885	1,043,233	15,740,029	13,006,257	13,710,609	208,652,915	33,019,616	23,520,453	6,599,503	4,151,725	34,271,681	62,904,858	16,267,181	1,063,185	80,235,224	347,528,438
2.850	3.150	2.500	2.500	80	152,254	4,304,212	883,496	5,187,708	26,937,359	43,900,155	43,900,155	1,537,083	1,043,367	15,742,054	13,006,119	13,609,279	209,392,632	33,147,104	23,539,895	6,621,405	4,151,725	34,313,026	62,956,856	16,321,168	1,063,185	80,341,209	348,139,669
2.900	3.000	2.550	2.550	80	152,254	4,379,725	879,101	5,258,825	26,937,359	43,900,155	43,900,155	1,546,929	1,050,051	15,842,900	12,999,215	13,910,025	208,388,344	33,107,999	23,505,334	6,581,854	4,151,725	34,238,913	62,864,421	16,223,678	1,063,185	80,151,284	347,589,605
2.900	3.050	2.525	2.525	80	152,254	4,379,725	880,609	5,260,333	26,937,359	43,900,155	43,900,155	1,547,138	1,050,192	15,845,031	12,999,069	13,805,675	209,126,465	33,219,317	23,522,621	6,602,756	4,151,725	34,277,102	62,910,655	16,275,200	1,063,185	80,249,040	348,179,523
2.900	3.100	2.500	2.500	80	152,254	4,379,725	882,073	5,261,798	26,937,359	43,900,155	43,900,155	1,547,340	1,050,329	15,847,099	12,998,927	13,702,882	209,869,919	33,337,307	23,541,625	6,624,494	4,151,725	34,317,844	62,961,481	16,328,782	1,063,185	80,353,448	348,784,544
2.950	3.000	2.525	2.525	80	152,254	4,455,237	879,101	5,334,338	26,937,359	43,900,155	43,900,155	1,557,308	1,057,096	15,949,189	12,991,938	13,902,238	209,603,629	33,427,461	23,525,228	6,606,174	4,151,725	34,283,128	62,917,630	16,283,625	1,063,185	80,264,440	348,840,458
2.950	3.050	2.500	2.500	80	152,254	4,455,237	880,609	5,335,846	26,937,359	43,900,155	43,900,155	1,557,514	1,057,236	15,951,304	12,991,793	13,797,948	210,350,851	33,537,007	23,543,792	6,627,747	4,151,725	34,323,265	62,967,278	16,336,801	1,063,185	80,367,264	349,439,967
3.000	3.000	2.500	2.500	80	152,254	4,530,750	866,173	5,396,922	26,937,359	43,900,155	43,900,155	1,565,850	1,062,894	16,036,678	12,985,948	13,895,829	210,855,458	33,745,151	23,546,400	6,631,165	4,151,725	34,329,291	62,974,253	16,345,226	1,063,185	80,382,664	350,097,739
3.050	4.300	3.650	0.000	80	101,503	4,606,262	781,694	5,387,956	22,272,462	36,297,712	36,297,712	1,564,630	1,062,066	16,024,177	12,986,804	17,437,535	312,644,619	24,434,895	23,686,036	6,564,847	4,370,237	34,621,120	63,347,706	16,181,757	1,119,142	80,648,605	401,187,864
3.100	4.250	3.650	0.000	80	101,503	4,681,775	779,825	5,461,600	22,272,462	36,297,712	36,297,712	1,574,623	1,068,849	16,126,528	12,979,797	17,538,780	313,358,087	23,827,557	23,701,908	6,575,726	4,370,237	34,647,870	63,390,154	16,208,572	1,119,142	80,717,868	401,513,965
3.150	4.200	3.650	0.000	80	101,503	4,757,287	777,921	5,535,208	22,272,462	36,297,712	36,297,712	1,584,541	1,075,582	16,228,100	12,972,843	17,641,393	314,076,884	23,284,440	23,718,176	6,586,764	4,370,237	34,675,177	63,433,663	16,235,781	1,119,142	80,788,586	401,888,095
3.200	4.150	3.650	0.000	80	101,503	4,832,800	783,442	5,616,242	22,272,462	36,297,712	36,297,712	1,595,379	1,082,938	16,339,092	12,965,244	17,744,442	314,784,106	22,803,541	23,734,844	6,597,962	4,370,237	34,703,043	63,478,241	16,263,384	1,119,142	80,860,766	402,309,454
3.250	4.100	3.650	0.000	80	101,503	4,557,718	781,518	5,339,236	22,272,462	36,297,712	36,297,712	1,557,978	1,057,551	15,956,056	12,991,468	17,895,414	316,318,862	22,382,851	23,751,914	6,609,321	4,370,237	34,731,472	63,523,893	16,291,382	1,119,142	80,934,417	402,756,463
3.300	4.050	3.650	0.000	80	101,503	4,627,837	795,147	5,422,984	22,272,462	36,297,712	36,297,712	1,569,392	1,065,298	16,072,951	12,983,465	18,000,901	317,026,657	22,020,367	23,769,388	6,620,841	4,370,237	34,760,466	63,570,628	16,319,778	1,119,142	81,009,548	403,267,611
3.350	4.000	3.650	0.000	80	101,503	4,697,956	793,263	5,491,218	22,272,462	36,297,712	36,297,712	1,578,623	1,071,564	16,167,486	12,976,993	18,109,907	317,775,991	21,714,082	23,787,270	6,632,523	4,370,237	34,790,029	63,618,452	16,348,572	1,119,142	81,086,167	403,820,965
3.400	3.950	3.650	0.000	80	101,503	4,768,075	791,340	5,559,415	22,272,462	36,297,712	36,297,712	1,587,787	1,077,785	16,261,346	12,970,567	18,220,417	318,530,762	21,461,992	23,805,562	6,644,367	4,370,237	34,820,165	63,667,374	16,377,766	1,119,142	81,164,282	404,415,938
3.450	3.900	3.650	0.000	80	101,503	4,838,193	814,571	5,652,764	22,272,462	36,297,712	36,297,712	1,600,236	1,086,235	16,388,840	12,961,839	18,329,140	319,233,172	21,262,089	23,824,267	6,656,373	4,370,237	34,850,877	63,717,400	16,407,361	1,119,142	81,243,902	405,052,321
3.500	3.850	3.650	0.000	80	101,503	4,908,312	839,867	5,748,179	22,272,462	36,297,712	36,297,712	1,612,848	1,094,796	16,518,003	12,952,996	18,439,154	319,936,814	21,112,368	23,843,387	6,668,543	4,370,237	34,882,167	63,768,538	16,437,358	1,119,142	81,325,038	405,727,835
3.550	3.800	3.650	0.000	80	101,503	4,978,431	838,274	5,816,704	22,272,462	36,297,712	36,297,712	1,621,837	1,100,898	16,610,066	12,946,693	18,554,290	320,707,453	21,010,824	23,862,927	6,680,877	4,370,237	34,914,041	63,820,797	16,467,760	1,119,142	81,407,699	406,439,929
3.600	3.750	3.650	0.000	80	101,503	5,048,549	836,644	5,885,194	22,272,462	36,297,712	36,297,712	1,630,765	1,106,958	16,701,507	12,940,433	18,671,049	321,483,628	20,955,452	23,882,889	6,693,375	4,370,237	34,946,501	63,874,185	16,498,567	1,119,142	81,491,893	407,188,512
3.650	3.700	3.650	0.000	80	-	5,118,668	834,977	5,953,645	-	-	-	1,639,634	1,112,978	16,792,334	12,934,215	18,789,463	322,265,371	20,944,245	23,903,277	6,706,038	4,370,237	34,979,552	63,928,710	16,529,781	1,119,142	81,577,632	344,659,379
3.700	3.650	3.650	0.000	80	50,751	4,842,868	833,272	5,676,139	16,091,078	26,223,834	26,223,834	1,603,336	1,088,340	16,420,589	12,959,665	18,955,825	323,843,034	20,975,197	23,924,092	6,718,867	4,370,237	35,013,196	63,984,381	16,561,403	1,119,142	81,664,926	391,193,163
3.750	3.650	3.600	0.000	80	50,751	4,601,543	833,272	5,434,814	16,091,078	26,223,834	26,223,834	1,570,997	1,066,388	16,089,386	12,982,340	18,988,991	327,044,558	21,042,758	23,923,037	6,733,165	4,370,237	35,026,439	63,981,559	16,596,646	1,119,142	81,697,346	393,022,342
3.800	3.650	3.550	0.000	80	101,503	4,388,608	833,272	5,221,880	22,272,462	36,297,712	36,297,712	1,541,823	1,046,585	15,790,601	13,002,795	19,018,910	330,242,146	21,146,564	23,924,052	6,748,585	4,370,237	35,042,874	63,984,274	16,634,655	1,119,142	81,738,070	412,507,758
3.850	3.650	3.500	0.000	80	101,503	4,199,334	833,272	5,032,605	22,272,462	36,297,712	36,297,712	1,515,356	1,028,619	15,519,535	13,021,353	19,046,054	333,443,941	21,284,711	23,927,151	6,765,132	4,370,237	35,062,520	63,992,563	16,675,441	1,119,142	81,787,145	414,474,151
3.900	3.650	3.450	0.000	80	101,503	3,828,483	833,272	4,661,755	22,272,462	36,297,712	36,297,712	1,461,919	992,346	14,972,266	13,058,820	19,100,857	337,187,297	21,455,292	23,932,349	6,782,810	4,370,237	35,085,396	64,006,463	16,719,017	1,119,142	81,844,622	416,526,639
3.950	3.650	3.400	0.000	80	101,503	3,692,920	833,272	4,526,192	22,272,462	36,297,712	36,297,712	1,441,825	978,706	14,766,468	13,072,909	19,121,465	340,384,808	21,656,402	23,939,659	6,801,626	4,370,237	35,111,522	64,026,015	16,765,395	1,119,142	81,910,552	418,626,825
4.000	3.650	3.350	0.000	80	101,503	3,414,478	833,272	4,247,749	22,272,462	36,297,712	36,297,712	1,399,524	949,992	14,333,240	13,102,569	19,164,847	344,045,301	21,886,136	23,949,099	6,821,583	4,370,237	35,140,919	64,051,262	16,814,589	1,119,142	81,984,993	420,816,439
4.050	3.650	3.300	0.000	80	101,503	3,313,111	833,272	4,146,382	22,272,462	36,297,712	36,297,712	1,383,760	939,292	14,171,792	13,113,622	19,181,014	347,275,563	22,142,588	23,960,686	6,842,689	4,370,237	35,173,611	64,082,249	16,866,612	1,119,142	82,068,003	423,043,344
4.100	3.650	3.250	0.000	80	101,503	3,096,012	833,272	3,929,284	22,272,462	36,297,712	36,297,712	1,349,294	915,897	13,818,816	13,137,787	19,216,360	350,911,694	22,423,851	23,974,436	6,864,949	4,370,237	35,209,622	64,119,025	16,921,481	1,119,142	82,159,648	425,361,095

Appendix A

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)	Maintenance over design life			Disruption time: Construction roadwork			Disruption time: Maintenance roadwork			Travel time during normal operations				Fuel Consumption				CO2 Emissions				
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	WLC - Dual carriagway per km
4.150	3.650	3.200	0.000	80	101,503	2,909,928	833,272	3,743,199	22,272,462	36,297,712	36,297,712	1,318,939	895,292	13,507,930	13,159,071	19,247,492	354,533,362	22,728,021	23,990,370	6,888,370	4,370,237	35,248,977	64,161,640	16,979,211	1,119,142	82,259,993	427,741,110
4.200	3.650	3.150	0.000	80	101,503	2,748,655	833,272	3,581,926	22,272,462	36,297,712	36,297,712	1,291,976	876,989	13,231,789	13,177,976	19,275,144	358,153,852	23,053,192	24,008,509	6,912,958	4,370,237	35,291,704	64,210,151	17,039,820	1,119,142	82,369,112	430,182,033
4.250	3.650	3.100	0.000	80	101,503	2,607,541	833,272	3,440,812	22,272,462	36,297,712	36,297,712	1,267,850	860,612	12,984,698	13,194,892	19,299,887	361,783,823	23,397,458	24,028,873	6,938,722	4,370,237	35,337,832	64,264,614	17,103,326	1,119,142	82,487,081	432,682,889
4.300	3.650	3.050	0.000	80	101,503	2,483,028	833,272	3,316,300	22,272,462	36,297,712	36,297,712	1,246,121	845,863	12,762,169	13,210,127	19,322,171	365,432,029	23,758,914	24,051,486	6,965,669	4,370,237	35,387,392	64,325,092	17,169,748	1,119,142	82,613,982	435,242,971
4.350	3.650	3.000	0.000	80	101,503	2,372,351	833,272	3,205,622	22,272,462	36,297,712	36,297,712	1,226,441	832,504	12,560,611	13,223,926	19,342,354	369,105,824	24,135,653	24,076,373	6,993,808	4,370,237	35,440,418	64,391,652	17,239,108	1,119,142	82,749,902	437,861,763
4.400	3.650	2.950	0.000	80	101,503	2,273,323	833,272	3,106,595	22,272,462	36,297,712	36,297,712	1,208,524	820,342	12,377,113	13,236,489	19,360,729	372,811,518	24,525,771	24,103,561	7,023,148	4,370,237	35,496,946	64,464,366	17,311,428	1,119,142	82,894,936	440,538,901
4.450	3.650	2.900	0.000	80	101,503	2,130,926	833,272	2,964,197	22,272,462	36,297,712	36,297,712	1,182,220	802,487	12,107,718	13,254,932	19,387,706	376,752,282	24,927,361	24,133,078	7,053,699	4,370,237	35,557,014	64,543,309	17,386,732	1,119,142	83,049,183	443,302,992
4.500	3.650	2.850	0.000	80	101,503	2,054,642	833,272	2,887,914	22,272,462	36,297,712	36,297,712	1,167,852	792,734	11,960,569	13,265,006	19,402,441	380,525,859	25,338,519	24,164,955	7,085,470	4,370,237	35,620,662	64,628,563	17,465,046	1,119,142	83,212,751	446,095,797
4.550	3.650	2.800	0.000	80	101,503	1,941,984	833,272	2,775,256	22,272,462	36,297,712	36,297,712	1,146,259	778,077	11,739,429	13,280,146	19,424,585	384,516,562	25,757,337	24,199,225	7,118,474	4,370,237	35,687,935	64,720,216	17,546,398	1,119,142	83,385,755	448,973,821
4.600	3.650	2.750	0.000	80	101,503	1,843,121	833,272	2,676,393	22,272,462	36,297,712	36,297,712	1,126,924	764,952	11,541,407	13,293,703	19,444,415	388,536,220	26,181,912	24,235,922	7,152,722	4,370,237	35,758,881	64,818,362	17,630,816	1,119,142	83,568,320	451,908,344
4.650	3.650	2.700	0.000	80	101,503	1,790,090	833,272	2,623,362	22,272,462	36,297,712	36,297,712	1,116,396	757,806	11,433,583	13,301,085	19,455,212	392,450,155	26,610,336	24,275,086	7,188,228	4,370,237	35,833,550	64,923,104	17,718,334	1,119,142	83,760,580	454,874,303
4.700	3.650	2.650	0.000	80	101,503	1,708,820	833,272	2,542,091	22,272,462	36,297,712	36,297,712	1,100,040	746,703	11,266,072	13,312,553	19,471,986	396,560,999	27,040,705	24,316,756	7,225,005	4,370,237	35,911,997	65,034,550	17,808,986	1,119,142	83,962,678	457,923,475
4.750	3.650	2.600	0.000	80	101,503	1,636,104	833,272	2,469,376	22,272,462	36,297,712	36,297,712	1,085,168	736,609	11,113,765	13,322,980	19,487,238	400,720,261	27,471,113	24,360,977	7,263,068	4,370,237	35,994,282	65,152,819	17,902,809	1,119,142	84,174,770	461,029,967
4.800	3.650	2.550	0.000	80	101,503	1,570,660	833,272	2,403,931	22,272,462	36,297,712	36,297,712	1,071,584	727,388	10,974,641	13,332,505	19,501,170	404,933,574	27,899,654	24,407,798	7,302,434	4,370,237	36,080,469	65,278,039	17,999,843	1,119,142	84,397,024	464,194,218
4.850	3.650	2.500	0.000	80	101,503	1,487,832	833,272	2,321,104	22,272,462	36,297,712	36,297,712	1,054,106	715,524	10,795,645	13,344,759	19,519,094	409,313,945	28,324,422	24,457,269	7,343,121	4,370,237	36,170,626	65,410,348	18,100,132	1,119,142	84,629,622	467,438,824
4.900	3.600	2.500	0.000	80	101,503	1,435,864	821,857	2,257,721	22,272,462	36,297,712	36,297,712	1,040,507	706,293	10,656,369	13,354,294	19,668,217	411,080,856	28,395,529	24,478,516	7,356,116	4,370,237	36,204,870	65,467,175	18,132,165	1,119,142	84,718,481	468,701,683
4.950	3.550	2.500	0.000	80	101,503	1,388,351	819,977	2,208,328	22,272,462	36,297,712	36,297,712	1,029,768	699,003	10,546,386	13,361,824	19,816,444	412,798,576	28,504,784	24,500,200	7,369,279	4,370,237	36,239,715	65,525,166	18,164,609	1,119,142	84,808,917	469,988,756
5.000	3.500	2.500	0.000	80	101,503	1,326,571	880,979	2,207,550	22,272,462	36,297,712	36,297,712	1,029,598	698,888	10,544,643	13,361,943	19,955,684	414,298,989	28,650,182	24,522,322	7,382,609	4,370,237	36,275,168	65,584,330	18,197,468	1,119,142	84,900,940	471,261,983
2.850	3.000	2.575	2.575	90	152,254	4,304,212	467,458	4,771,670	26,937,359	43,900,155	43,900,155	1,662,734	501,626	15,136,808	14,678,499	6,878,120	206,698,498	32,539,000	23,331,645	6,551,596	4,151,725	34,034,966	62,399,896	16,149,093	1,063,185	79,612,174	340,936,011
2.850	3.050	2.550	2.550	90	152,254	4,304,212	467,823	4,772,036	26,937,359	43,900,155	43,900,155	1,662,793	501,644	15,137,351	14,678,458	6,826,579	207,415,037	32,661,619	23,350,284	6,572,111	4,151,725	34,074,119	62,449,745	16,199,662	1,063,185	79,712,591	341,554,767
2.850	3.100	2.525	2.525	90	152,254	4,304,212	468,177	4,772,390	26,937,359	43,900,155	43,900,155	1,662,851	501,661	15,137,877	14,678,417	6,775,806	208,136,585	32,790,868	23,370,570	6,593,463	4,151,725	34,115,759	62,504,001	16,252,293	1,063,185	79,819,479	342,187,743
2.850	3.150	2.500	2.500	90	152,254	4,304,212	472,097	4,776,309	26,937,359	43,900,155	43,900,155	1,663,491	501,855	15,143,707	14,677,968	6,725,594	208,857,362	32,927,390	23,392,512	6,615,655	4,151,725	34,159,892	62,562,682	16,306,995	1,063,185	79,932,862	342,837,569
2.900	3.000	2.550	2.550	90	152,254	4,379,725	467,458	4,847,183	26,937,359	43,900,155	43,900,155	1,675,023	505,333	15,248,685	14,669,883	6,874,082	207,882,594	32,859,876	23,350,271	6,575,248	4,151,725	34,077,244	62,449,712	16,207,394	1,063,185	79,720,291	342,166,745
2.900	3.050	2.525	2.525	90	152,254	4,379,725	467,823	4,847,548	26,937,359	43,900,155	43,900,155	1,675,082	505,351	15,249,224	14,669,841	6,822,572	208,607,817	32,981,082	23,370,179	6,596,431	4,151,725	34,118,335	62,502,953	16,259,609	1,063,185	79,825,746	342,795,014
2.900	3.100	2.500	2.500	90	152,254	4,379,725	468,177	4,847,902	26,937,359	43,900,155	43,900,155	1,675,139	505,369	15,249,746	14,669,801	6,771,828	209,338,139	33,108,558	23,391,742	6,618,454	4,151,725	34,161,921	62,560,624	16,313,894	1,063,185	79,937,703	343,437,353
2.950	3.000	2.525	2.525	90	152,254	4,455,237	467,458	4,922,695	26,937,359	43,900,155	43,900,155	1,687,211	509,010	15,359,640	14,661,337	6,870,078	209,082,763	33,179,339	23,370,166	6,599,568	4,151,725	34,121,459	62,502,920	16,267,341	1,063,185	79,833,446	343,411,268
2.950	3.050	2.500	2.500	90	152,254	4,455,237	467,823	4,923,061	26,937,359	43,900,155	43,900,155	1,687,270	509,028	15,360,175	14,661,296	6,818,598	209,816,836	33,298,772	23,391,350	6,621,422	4,151,725	34,164,497	62,559,576	16,321,210	1,063,185	79,943,971	344,048,950
3.000	3.000	2.500	2.500	90	152,254	4,530,750	467,458	4,998,208	26,937,359	43,900,155	43,900,155	1,699,300	512,658	15,469,696	14,652,861	6,866,106	210,299,290	33,497,029	23,391,338	6,624,559	4,151,725	34,167,622	62,559,543	16,328,942	1,063,185	79,951,670	344,669,575
3.050	4.300	3.650	0.000	90	101,503	4,606,262	437,425	5,043,687	22,272,462	36,297,712	36,297,712	1,706,535	514,840	15,535,553	14,647,788	8,169,415	303,956,822	24,183,448	23,330,229	6,454,727	4,370,237	34,155,192	62,396,108	15,910,320	1,119,142	79,425,570	388,205,492
3.100	4.250	3.650	0.000	90	101,503	4,681,775	434,590	5,116,365	22,272,462	36,297,712	36,297,712	1,718,024	518,306	15,640,146	14,639,733	8,216,763	304,679,624	23,591,254	23,340,201	6,464,511	4,370,237	34,174,948	62,422,778	15,934,437	1,119,142	79,476,356	388,493,938
3.150	4.200	3.650	0.000	90	101,503	4,757,287	433,998	5,191,285	22,272,462	36,297,712	36,297,712	1,729,777	521,852	15,747,143	14,631,492	8,264,611	305,402,808	23,061,680	23,350,554	6,474,472	4,370,237	34,195,263	62,450,468	15,958,991	1,119,142	79,528,600	388,829,267
3.200	4.150	3.650	0.000	90	101,503	4,832,800	433,394	5,266,193	22,272,462	36,297,712	36,297,712	1,741,439	525,370	15,853,306	14,623,315	8,313,111	306,131,600	22,592,772	23,361,291	6,484,611	4,370,237	34,216,139	62,479,183	15,983,983	1,119,142	79,582,307	389,209,960
3.250	4.100	3.650	0.000	90	101,503	4,908,312	432,776	5,341,088	22,272,462	36,297,712	36,297,712	1,753,011	528,861	15,958,652	14,615,201	8,362,275	306,866,021	22,182,573	23,372,413	6,494,928	4,370,237	34,237,578	62,508,928	16,009,414	1,119,142	79,637,484	389,634,754
3.300	4.050	3.650	0.000	90	101,503	4,983,824	434,506	5,418,331	22,272,462	36,297,712	36,297,712	1,764,855	532,435	16,066,482	14,606,896	8,411,969	307,600,766	21,829,127	23,383,922	6,505,424	4,370,237	34,259,583	62,539,709	16,035,286	1,119,142	79,694,136	390,102,647
3.350	4.000	3.650	0.000	90	101,503	5,059,337	436,294	5,495,631	22,272,462	36,297,712	36,297,712	1,776,620	535,984	16,173,578	14,598,648	8,462,348	308,341,075	21,530,480	23,395,820	6,516,100	4,370,237	34,282,156	62,571,530	16,061,599	1,119,142	79,752,271	390,612,120
3.400	3.950	3.650	0.000	90	101,503	4,768,075	438,143	5,206,218	22,272,462	36,297,712	36,297,712	1,732,109	522,556	15,768,371	14,629,857	8,536,415	309,921,671	21,284,675	23,408,109	6,526,954	4,370,237	34,305,301	62,604,398	16,088,355	1,119,142	79,811,895	391,125,637
3.450	3.900	3.650	0.000	90	101,503	4,838,193	437,541	5,275,734	22,272,462	36,297,712	36,297,712	1,742,918	525,817	15,866,771	14,622,278	8,588,684	310,687,581	21,089,757	23,420,792	6,537,990	4,370,237	34,329,019	62,638,318	16,115,556	1,119,142	79,873,016	391,713,974
3.500	3.850	3.650	0.000	90	101,503	4,908,312	439,465	5,347,777	22,272,462	36,297,712	36,297,712	1,754,040	529,172	15,968,022	14,614,480	8,641,522	311,453,404	20,943,770	23,433,871	6,549,205	4,370,237	34,353,313	62,673,296	16,143,202	1,119,142	79,935,639	392,340,352
3.550	3.800	3.650	0.000	90	101,503	4,978,431	441,458	5,419,888	22,272,462	36,297,712	36,297,712	1,765,093	532,507	16,068,648	14,606,730	8,695,100	312,224,868	20,844,758	23,447,347	6,560,603	4,370,237	34,378,186	62,709,337	16,171,295	1,119,142	79,999,774	393,003,294
3.600	3.750	3.650	0.000	90	101,503	5,048,549	440,866	5,489,416	22,272,462	36,297,712	36,297,712	1,775,677	535,700	16,164,996	14,599,309	8,749,602	313,008,050	20,790,766	23,461,223	6,572,182	4,370,237	34,403,641	62,746,448	16,199,836	1,119,142	80,065,426	393,701,315
3.650	3.700	3.650	0.000	90	-	5,118,668	442,945	5,561,613	-	-	-	1,786,592	538,992	16,264,362	14,591,656	8,804,708	313,790,977	20,779,838	23,475,501	6,583,943	4,370,237	34,429,681	62,784,635	16,228,828	1,119,142	80,132,605	331,120,683
3.700	3.650	3.650	0.000	90	50,751	4,842,868	439,640	5,282,508	16,091,078	26,223,834	26,223,834	1,743,967	526,133	15,876,322	14,621,542	8,883,379	315,388,396	20,810,019	23,490,184	6,595,888	4,370,237	34,456,309	62,823,905	16,258,270	1,119,142	80,201,317	377,586,260
3.750	3.650	3.600	0.000	90	50,751	4,601,543	439,640	5,041,183	16,091,078	26,223,834	26,223,834	1,706,137	514,720	15,531,935	14,648,067	8,899,494	318,452,073	20,877,580	23,489,129	6,610,186	4,370,237	34,469,551	62,821,083	16,293,513	1,119,142	80,233,737	379,309,317
3.800	3.650	3.550	0.000	90	101,503	4,388,608	439,640	4,828,249	22,272,462	36,297,712	36,297,712	1,671,951	504,407	15,220,720	14,672,037	8,914,057	321,508,468	20,981,386	23,490,144	6,625,606	4,370,237	34,485,987	62,823,798	16,331,522	1,119,142	80,274,461	398,687,407
3.850	3.650	3.500	0.000	90	101,503	4,199,334	439,640	4,638,974	22,272,462	36,297,712	36,297,712	1,640,885	495,034	14,937,907	14,693,819	8,927,291	324,565,520	21,119,533	23,493,243	6,642,153	4,370,237	34,505,633	62,832,086	16,372,308	1,119,142	80,323,536	400,545,013
3.900	3.650	3.450	0.000	90	101,503	4,029,982	439,640	4,469,623	22,272,462	36,297,712	36,297,712	1,612,513	486,475	14,679,623	14,713,712	8,939,377	327,629,885	21,290,114	23,498,441	6,659,831	4,370,237	34,528,508	62,845,987	16,415,884	1,119,142	80,381,012	402,466,821
3.950	3.650	3.400	0.000	90	101,503	3,692,920	439,640	4,132,561	22,272,462	36,297,712	36,297,712	1,554,294	468,911	14,149,617	14,754,532	8,964,178	331,213,949	21,491,224	23,505,751	6,678,646	4,370,237	34,554,634	62,865,539	16,462,262	1,119,142	80,446,943	404,466,821
4.000	3.650	3.350	0.000	90	101,503	3,569,681	439,640	4,009,322	22,272,462	36,297,712	36,297,712	1,532,380	462,300	13,950,125	14,769,897	8,973,513	334,280,722	21,720,958	23,515,191	6,698,604	4,370,237	34,584,032	62,890,786	16,511,456	1,119,142	80,521,384	406,516,014
4.050	3.650	3.300	0.000	90	101,503	3,313,111	439,640	3,752,751	22,272,462	36,297,712	36,297,712	1,485,581	448,181	13,524,085	14,802,711	8,993,449	337,796,442	21,977,410	23,526,778	6,719,710	4,370,237	34,616,724	62,921,773	16,563,479	1,119,142	80,604,394	408,647,410
4.100	3.650	3.250	0.000	90	101,503	3,219,853	439,640	3,659,493	22,272,462	36,297,712	36,297,712	1,468,151	442,923	13,365,409	14,814,932	9,000,874	340,897,010	22,258,673	23,540,528	6,741,970	4,370,237	34,652,735	62,958,549	16,618,348	1,119,142	80,696,039	410,817,084
4.150	3.650	3.200	0.000	90	101,503	3,017,703	439,640	3,457,343	22,272,462	36,297,712	36,297,712	1,429,540	431,274	13,013,918	14,842,003	9,017,321	344,394,364	22,562,843	23,556,462	6,765,390	4,370,237	34,692,090	63,001,164	16,676,078	1,119,142	80,796,384	413,070,981
4.200	3.650	3.150	0.000	90	101,503	2,843,436	439,640	3,283,076	22,272,462	36,297,712	36,297,712	1,395,282	420,939	12,702,044	14,866,024	9,031,915	347,879,686	22,888,014	23,574,601	6,789,979	4,370,237	34,734,816	63,049,674	16,736,687	1,119,142	80,905,503	415,384,459
4.250	3.650	3.100	0.000	90	101,503	2,691,655	439,640	3,131,295	22,272,462	36,297,712	36,297,712	1,364,648	411,697	12,423,170	14,887,503	9,044,965	351,364,696	23,232,280	23,594,965	6,815,743	4,370,237	34,780,944	63,104,138	16,800,193	1,119,142	81,023,472	417,756,040
4.300	3.650	3.050	0.000	90	101,503	2,558,272	439,640	2,997,912	22,272,462	36,297,712	36,297,712	1,337,070	403,377	12,172,111	14,906,839	9,056,713	354,858,891	23,593,736	23,617,578	6,842,690	4,370,237	34,830,505	63,164,616	16,866,615	1,119,142	81,150,373	420,184,610
4.350	3.650	3.000	0.000	90	101,503	2,440,132	439,640	2,879,772	22,272,462	36,297,712	36,297,712	1,312,095	395,843	11,944,744	14,924,351	9,067,352	358,370,137	23,970,475	23,642,465	6,870,829	4,370,237	34,883,531	63,231,176	16,935,975	1,119,142	81,286,293	422,669,321
4.400	3.650	2.950	0.000	90	101,503	2,334,765	439,640	2,774,405	22,272,462	36,297,712	36,297,712	1,289,356	388,983	11,737,741	14,940,294	9,077,038	361,905,092	24,360,593	23,669,653	6,900,169	4,370,237	34,940,059	63,303,890	17,008,295	1,119,142	81,431,326	425,209,517
4.450	3.650	2.900	0.000	90	101,503	2,240,204	439,640	2,679,844	22,272,462	36,297,712	36,297,712	1,268,556	382,707	11,548,384	14,954,878	9,085,899	365,469,501	24,762,183	23,699,170	6,930,719	4,370,237	35,000,126	63,382,832	17,083,599	1,119,142	81,585,573	427,804,694
4.500	3.650	2.850	0.000	90	101,503	2,154,869	439,640	2,594,509	22,272,462	36,297,712	36,297,712	1,249,448	376,943	11,374,432	14,968,276	9,094,039	369,068,413	25,173,341	23,731,047	6,962,491	4,370,237	35,063,775	63,468,086	17,161,913	1,119,142	81,749,141	430,454,470
4.550	3.650	2.800	0.000	90	101,503	2,030,256	439,640	2,469,897	22,272,462	36,297,712	36,297,712	1,220,935	368,341	11,114,865	14,988,268	9,106,185	372,896,334	25,592,159	23,765,317	6,995,495	4,370,237	35,131,048	63,559,740	17,243,265	1,119,142	81,922,146	433,186,377
4.600	3.650	2.750	0.000	90	101,503	1,963,325	439,640	2,402,965	22,272,462	36,297,712	36,297,712	1,205,305	363,625	10,972,571	14,999,227	9,112,843	376,567,207	26,016,734	23,802,014	7,029,743	4,370,237	35,201,994	63,657,886	17,327,683	1,119,142	82,104,711	435,944,381
4.650	3.650	2.700	0.000	90	101,503	1,863,155	439,640	2,302,795	22,272,462	36,297,712	36,297,712	1,181,473	356,436	10,755,624	15,015,936	9,122,995	380,451,231	26,445,158	23,841,178	7,065,248	4,370,237	35,276,663	63,762,628	17,415,201	1,119,142	82,296,971	438,783,115
4.700	3.650	2.650	0.000	90	101,503	1,774,544	439,640	2,214,184	22,272,462	36,297,712	36,297,712	1,159,929	349,936	10,559,493	15,031,042	9,132,173	384,366,309	26,875,527	23,882,848	7,102,025	4,370,237	35,355,110	63,874,074	17,505,853	1,119,142	82,499,069	441,674,774
4.750	3.650	2.600	0.000	90	101,503	1,695,599	439,640	2,135,239	22,272,462	36,297,712	36,297,712	1,140,346	344,028	10,381,217	15,044,773	9,140,515	388,319,199	27,305,935	23,927,069	7,140,089	4,370,237	35,437,395	63,992,343	17,599,676	1,119,142	82,711,161	444,619,464
4.800	3.650	2.550	0.000	90	101,503	1,653,326	439,640	2,092,966	22,272,462	36,297,712	36,297,712	1,129,702	340,817	10,284,315	15,052,236	9,145,049	392,183,507	27,734,476	23,973,890	7,179,455	4,370,237	35,523,581	64,117,563	17,696,710	1,119,142	82,933,415	447,592,968
4.850	3.650	2.500	0.000	90	101,503	1,587,021	439,640	2,026,661	22,272,462	36,297,712	36,297,712	1,112,773	335,710	10,130,204	15,064,106	9,152,261	396,237,449	28,159,244	24,023,361	7,220,142	4,370,237	35,613,739	64,249,872	17,796,999	1,119,142	83,166,013	450,645,032
4.900	3.600	2.500	0.000	90	101,503	1,503,171	441,748	1,944,919	22,272,462	36,297,712	36,297,712	1,091,493	329,290	9,936,482	15,079,026	9,224,726	398,103,912	28,228,578	24,038,451	7,232,270	4,370,237	35,640,958	64,290,231	17,826,894	1,119,142	83,236,267	451,856,692
4.950	3.550	2.500	0.000	90	101,503	1,450,516	443,936	1,894,453	22,272,462	36,297,712	36,297,712	1,078,118	325,255	9,814,716	15,088,405	9,294,786	399,837,436	28,335,109	24,053,951	7,244,583	4,370,237	35,668,771	64,331,686	17,857,244	1,119,142	83,308,071	453,076,338
5.000	3.500	2.500	0.000	90	101,503	1,402,375	452,081	1,854,456	22,272,462	36,297,712	36,297,712	1,067,382	322,016	9,716,983	15,095,932	9,364,682	401,534,707	28,476,881	24,069,864	7,257,080	4,370,237	35,697,181	64,374,244	17,888,049	1,119,142	83,381,435	454,320,696
2.850	3.000	2.575	2.575	95	152,254	4,662,896	279,146	4,942,042	26,937,359	43,900,155	43,900,155	1,784,224	254,974	15,387,922	15,473,556	3,413,865	205,959,976	32,414,938	23,257,175	6,549,066	4,151,725	33,957,966	62,200,729	16,142,859	1,063,185	79,406,772	338,590,774
2.850	3.050	2.550	2.550	95	152,254	4,662,896	277,229	4,940,125	26,937,359	43,900,155	43,900,155	1,783,900	254,927	15,385,122	15,473,784	3,388,343	206,672,431	32,542,502	23,276,985	6,569,700	4,151,725	33,998,410	62,253,710	16,193,718	1,063,185	79,510,613	339,226,721
2.850	3.100	2.525	2.525	95	152,254	4,662,896	274,158	4,937,054	26,937,359	43,900,155	43,900,155	1,783,380	254,853	15,380,636	15,474,149	3,363,230	207,391,648	32,676,493	23,298,412	6,591,172	4,151,725	34,041,308	62,311,014	16,246,645	1,063,185	79,620,844	339,875,680
2.850	3.150	2.500	2.500	95	152,254	4,662,896	272,444	4,935,340	26,937,359	43,900,155	43,900,155	1,783,089	254,812	15,378,132	15,474,352	3,338,454	208,113,689	32,817,533	23,321,462	6,613,486	4,151,725	34,086,672	62,372,661	16,301,647	1,063,185	79,737,492	340,539,658

CONFIGURATION: LANE WIDTHS (m)				MPR (%)	COMPONENTS OF WHOLE-LIFE CYCLE COSTS (£)																		CO2 Emissions				WLC - Dual carriageway per km
						Maintenance over design life			Disruption time: Construction roadwork			Disruption time: Maintenance roadwork			Travel time during normal operations				Fuel Consumption								
Lane 1: CAT	Lane 2: MT	Lane 3: PC1	Lane 4: PC2		Initial Construction (A)	CAT Lane (B)	MT Lane (C)	Combined (B+C) = (D)	MT Lane (E)	PC Lane 1 (F)	PC Lane 2 (G)	CAT (H)	MT (I)	PC (J)	CAT (K)	MT (L)	PC (M)	Accidents (N)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	Diesel (O)	Petrol (P)	Electric (Q)	Sub-total (O+P+Q) = (R)	
2.900	3.000	2.550	2.550	95	152,254	4,744,702	279,146	5,023,847	26,937,359	43,900,155	43,900,155	1,798,015	256,945	15,506,863	15,463,887	3,411,732	207,129,033	32,735,815	23,275,802	6,572,719	4,151,725	34,000,245	62,250,544	16,201,160	1,063,185	79,514,888	339,820,796
2.900	3.050	2.525	2.525	95	152,254	4,744,702	277,229	5,021,930	26,937,359	43,900,155	43,900,155	1,797,694	256,899	15,504,087	15,464,112	3,386,225	207,850,021	32,861,964	23,296,880	6,594,020	4,151,725	34,042,625	62,306,918	16,253,665	1,063,185	79,623,768	340,466,167
2.900	3.100	2.500	2.500	95	152,254	4,744,702	274,158	5,018,860	26,937,359	43,900,155	43,900,155	1,797,178	256,825	15,499,640	15,464,474	3,361,128	208,577,858	32,994,184	23,319,583	6,616,163	4,151,725	34,087,471	62,367,638	16,308,246	1,063,185	79,739,068	341,124,406
2.950	3.000	2.525	2.525	95	152,254	4,826,507	279,146	5,105,653	26,937,359	43,900,155	43,900,155	1,811,688	258,899	15,624,779	15,454,300	3,409,617	208,314,048	33,055,278	23,295,697	6,597,039	4,151,725	34,044,460	62,303,753	16,261,107	1,063,185	79,628,044	341,064,459
2.950	3.050	2.500	2.500	95	152,254	4,826,507	277,229	5,103,736	26,937,359	43,900,155	43,900,155	1,811,369	258,853	15,622,028	15,454,524	3,384,126	209,043,734	33,179,655	23,318,052	6,619,011	4,151,725	34,088,788	62,363,542	16,315,266	1,063,185	79,741,992	341,719,151
3.000	3.000	2.500	2.500	95	152,254	4,908,312	279,146	5,187,458	26,937,359	43,900,155	43,900,155	1,825,244	260,836	15,741,697	15,444,795	3,407,520	209,515,298	33,372,968	23,316,868	6,622,030	4,151,725	34,090,623	62,360,376	16,322,707	1,063,185	79,746,268	342,321,753
3.050	4.300	3.650	0.000	95	101,503	4,606,262	260,565	4,866,827	22,272,462	36,297,712	36,297,712	1,771,437	253,146	15,277,637	15,482,522	3,962,503	299,892,933	24,057,724	23,188,303	6,407,483	4,370,237	33,966,022	62,016,531	15,793,868	1,119,142	78,929,541	382,286,453
3.100	4.250	3.650	0.000	95	101,503	4,681,775	260,754	4,942,529	22,272,462	36,297,712	36,297,712	1,784,307	254,986	15,388,632	15,473,499	3,985,337	300,611,205	23,473,102	23,195,457	6,416,657	4,370,237	33,982,351	62,035,664	15,816,482	1,119,142	78,971,288	382,557,749
3.150	4.200	3.650	0.000	95	101,503	4,757,287	259,307	5,016,594	22,272,462	36,297,712	36,297,712	1,796,797	256,771	15,496,359	15,464,741	4,008,532	301,338,949	22,950,300	23,202,985	6,426,018	4,370,237	33,999,240	62,055,798	15,839,556	1,119,142	79,014,496	382,874,778
3.200	4.150	3.650	0.000	95	101,503	4,832,800	257,842	5,090,641	22,272,462	36,297,712	36,297,712	1,809,188	258,541	15,603,217	15,456,053	4,032,044	302,072,436	22,487,387	23,210,889	6,435,566	4,370,237	34,016,692	62,076,936	15,863,091	1,119,142	79,059,169	383,236,505
3.250	4.100	3.650	0.000	95	101,503	4,908,312	257,177	5,165,489	22,272,462	36,297,712	36,297,712	1,821,615	260,317	15,710,395	15,447,340	4,055,854	302,809,823	22,082,433	23,219,170	6,445,302	4,370,237	34,034,708	62,099,084	15,887,089	1,119,142	79,105,314	383,641,785
3.300	4.050	3.650	0.000	95	101,503	4,983,824	255,674	5,239,499	22,272,462	36,297,712	36,297,712	1,833,809	262,060	15,815,566	15,438,790	4,080,016	303,554,867	21,733,507	23,227,830	6,455,225	4,370,237	34,053,292	62,122,245	15,911,549	1,119,142	79,152,936	384,089,154
3.350	4.000	3.650	0.000	95	101,503	5,059,337	254,977	5,314,314	22,272,462	36,297,712	36,297,712	1,846,044	263,808	15,921,083	15,430,211	4,104,489	304,303,862	21,438,679	23,236,871	6,465,337	4,370,237	34,072,444	62,146,424	15,936,474	1,119,142	79,202,040	384,577,576
3.400	3.950	3.650	0.000	95	101,503	5,134,849	254,267	5,389,116	22,272,462	36,297,712	36,297,712	1,858,185	265,543	16,025,795	15,421,698	4,129,301	305,058,697	21,196,017	23,246,294	6,475,638	4,370,237	34,092,168	62,171,626	15,961,864	1,119,142	79,252,632	385,105,695
3.450	3.900	3.650	0.000	95	101,503	4,838,193	254,384	5,092,578	22,272,462	36,297,712	36,297,712	1,809,510	258,587	15,606,000	15,455,827	4,165,938	306,664,192	21,003,591	23,256,101	6,486,128	4,370,237	34,112,466	62,197,855	15,987,722	1,119,142	79,304,719	385,628,531
3.500	3.850	3.650	0.000	95	101,503	4,908,312	253,651	5,161,963	22,272,462	36,297,712	36,297,712	1,821,032	260,234	15,705,365	15,447,749	4,191,611	307,439,491	20,859,471	23,266,294	6,496,808	4,370,237	34,133,339	62,225,117	16,014,047	1,119,142	79,358,306	386,231,966
3.550	3.800	3.650	0.000	95	101,503	4,978,431	257,263	5,235,694	22,272,462	36,297,712	36,297,712	1,833,185	261,971	15,810,179	15,439,228	4,217,510	308,210,695	20,761,725	23,276,875	6,507,679	4,370,237	34,154,791	62,253,415	16,040,843	1,119,142	79,413,399	386,871,843
3.600	3.750	3.650	0.000	95	101,503	5,048,549	254,757	5,303,306	22,272,462	36,297,712	36,297,712	1,844,250	263,552	15,905,607	15,431,469	4,243,969	309,001,914	20,708,423	23,287,846	6,518,741	4,370,237	34,176,823	62,282,756	16,068,109	1,119,142	79,470,006	387,545,806
3.650	3.700	3.650	0.000	95	-	5,118,668	254,888	5,373,556	-	-	-	1,855,667	265,183	16,004,077	15,423,464	4,270,722	309,793,043	20,697,635	23,299,208	6,529,994	4,370,237	34,199,439	62,313,144	16,095,847	1,119,142	79,528,133	324,940,613
3.700	3.650	3.650	0.000	95	50,751	4,842,868	255,933	5,098,801	16,091,078	26,223,834	26,223,834	1,810,547	258,736	15,614,942	15,455,100	4,308,894	311,387,752	20,727,430	23,310,964	6,541,439	4,370,237	34,222,640	62,344,586	16,124,059	1,119,142	79,587,787	371,374,751
3.750	3.650	3.600	0.000	95	50,751	4,601,543	255,933	4,857,476	16,091,078	26,223,834	26,223,834	1,769,840	252,918	15,263,863	15,483,642	4,316,851	314,388,022	20,794,991	23,309,909	6,555,737	4,370,237	34,235,883	62,341,763	16,159,302	1,119,142	79,620,207	373,048,793
3.800	3.650	3.550	0.000	95	101,503	4,388,608	255,933	4,644,542	22,272,462	36,297,712	36,297,712	1,733,020	247,657	14,946,313	15,509,459	4,324,049	317,379,523	20,898,797	23,310,924	6,571,157	4,370,237	34,252,318	62,344,478	16,197,311	1,119,142	79,660,931	392,377,330
3.850	3.650	3.500	0.000	95	101,503	4,199,334	255,933	4,455,267	22,272,462	36,297,712	36,297,712	1,699,531	242,871	14,657,491	15,532,939	4,330,595	320,370,098	21,036,944	23,314,023	6,587,704	4,370,237	34,271,964	62,352,767	16,238,097	1,119,142	79,710,006	394,184,730
3.900	3.650	3.450	0.000	95	101,503	4,029,982	255,933	4,285,916	22,272,462	36,297,712	36,297,712	1,668,921	238,497	14,393,497	15,554,402	4,336,579	323,366,320	21,207,525	23,319,221	6,605,382	4,370,237	34,294,840	62,366,667	16,281,673	1,119,142	79,767,482	396,055,578
3.950	3.650	3.400	0.000	95	101,503	3,877,566	255,933	4,133,500	22,272,462	36,297,712	36,297,712	1,640,818	234,480	14,151,125	15,574,106	4,342,073	326,373,784	21,408,635	23,326,531	6,624,198	4,370,237	34,320,966	62,386,220	16,328,051	1,119,142	79,833,413	397,988,193
4.000	3.650	3.350	0.000	95	101,503	3,569,681	255,933	3,825,615	22,272,462	36,297,712	36,297,712	1,582,320	226,121	13,646,609	15,615,123	4,353,508	329,880,129	21,638,369	23,335,971	6,644,155	4,370,237	34,350,363	62,411,467	16,377,245	1,119,142	79,907,853	399,996,932
4.050	3.650	3.300	0.000	95	101,503	3,457,159	255,933	3,713,092	22,272,462	36,297,712	36,297,712	1,560,319	222,977	13,456,866	15,630,548	4,357,809	332,898,631	21,894,821	23,347,558	6,665,261	4,370,237	34,383,055	62,442,454	16,429,268	1,119,142	79,990,864	402,052,247
4.100	3.650	3.250	0.000	95	101,503	3,219,853	255,933	3,475,786	22,272,462	36,297,712	36,297,712	1,512,729	216,176	13,046,431	15,663,916	4,367,112	336,352,032	22,176,084	23,361,308	6,687,521	4,370,237	34,419,066	62,479,229	16,484,137	1,119,142	80,082,509	404,187,486
4.150	3.650	3.200	0.000	95	101,503	3,133,768	255,933	3,389,702	22,272,462	36,297,712	36,297,712	1,495,041	213,648	12,893,879	15,676,318	4,370,569	339,408,763	22,480,254	23,377,242	6,710,942	4,370,237	34,458,421	62,521,845	16,541,867	1,119,142	80,182,854	406,359,226
4.200	3.650	3.150	0.000	95	101,503	2,944,987	255,933	3,200,921	22,272,462	36,297,712	36,297,712	1,455,396	207,983	12,551,967	15,704,115	4,378,319	342,852,694	22,805,425	23,395,381	6,735,530	4,370,237	34,501,148	62,570,355	16,602,476	1,119,142	80,291,973	408,612,886
4.250	3.650	3.100	0.000	95	101,503	2,781,377	255,933	3,037,310	22,272,462	36,297,712	36,297,712	1,420,021	202,928	12,246,875	15,728,919	4,385,234	346,288,781	23,149,691	23,415,745	6,761,294	4,370,237	34,547,276	62,624,818	16,665,982	1,119,142	80,409,942	410,924,243
4.300	3.650	3.050	0.000	95	101,503	2,638,218	255,933	2,894,151	22,272,462	36,297,712	36,297,712	1,388,228	198,384	11,972,678	15,751,210	4,391,449	349,727,519	23,511,147	23,438,358	6,788,242	4,370,237	34,596,836	62,685,297	16,732,404	1,119,142	80,536,843	413,291,890
4.350	3.650	3.000	0.000	95	101,503	2,511,901	255,933	2,767,834	22,272,462	36,297,712	36,297,712	1,359,474	194,275	11,724,695	15,771,371	4,397,070	353,177,500	23,887,886	23,463,245	6,816,380	4,370,237	34,649,862	62,751,857	16,801,764	1,119,142	80,672,763	415,714,747
4.400	3.650	2.950	0.000	95	101,503	2,399,619	255,933	2,655,553	22,272,462	36,297,712	36,297,712	1,333,325	190,538	11,499,170	15,789,706	4,402,182	356,645,912	24,278,004	23,490,433	6,845,720	4,370,237	34,706,390	62,824,570	16,874,084	1,119,142	80,817,796	418,191,976
4.450	3.650	2.900	0.000	95	101,503	2,299,157	255,933	2,555,090	22,272,462	36,297,712	36,297,712	1,309,426	187,123	11,293,053	15,806,463	4,406,854	360,138,887	24,679,594	23,519,950	6,876,271	4,370,237	34,766,458	62,903,513	16,949,388	1,119,142	80,972,043	420,722,920
4.500	3.650	2.850	0.000	95	101,503	2,208,740	255,933	2,464,674	22,272,462	36,297,712	36,297,712	1,287,486	183,988	11,103,836	15,821,846	4,411,143	363,661,761	25,090,752	23,551,827	6,908,042	4,370,237	34,830,106	62,988,767	17,027,702	1,119,142	81,135,611	423,307,060
4.550	3.650	2.800	0.000	95	101,503	2,077,472	255,933	2,333,405	22,272,462	36,297,712	36,297,712	1,254,858	179,325	10,822,441	15,844,723	4,417,521	367,420,964	25,509,570	23,586,097	6,941,046	4,370,237	34,897,379	63,080,420	17,109,054	1,119,142	81,308,616	425,972,128
4.600	3.650	2.750	0.000	95	101,503	2,006,954	255,933	2,262,888	22,272,462	36,297,712	36,297,712	1,236,928	176,763	10,667,798	15,857,295	4,421,026	371,006,420	25,934,145	23,622,794	6,975,294	4,370,237	34,968,325	63,178,567	17,193,473	1,119,142	81,491,181	428,661,438
4.650	3.650	2.700	0.000	95	101,503	1,901,971	255,933	2,157,904	22,272,462	36,297,712	36,297,712	1,209,674	172,868	10,432,754	15,876,404	4,426,353	374,811,008	26,362,569	23,661,958	7,010,800	4,370,237	35,042,994	63,283,308	17,280,991	1,119,142	81,683,441	431,430,239
4.700	3.650	2.650	0.000	95	101,503	1,845,525	255,933	2,101,459	22,272,462	36,297,712	36,297,712	1,194,730	170,732	10,303,865	15,886,882	4,429,275	378,479,399	26,792,938	23,703,628	7,047,577	4,370,237	35,121,441	63,394,755	17,371,642	1,119,142	81,885,539	434,223,766
4.750	3.650	2.600	0.000	95	101,503	1,759,584	255,933	2,015,517	22,272,462	36,297,712	36,297,712	1,171,560	167,421	10,104,041	15,903,128	4,433,804	382,353,977	27,223,346	23,747,849	7,085,640	4,370,237	35,203,726	63,513,024	17,465,465	1,119,142	82,097,631	437,095,693
4.800	3.650	2.550	0.000	95	101,503	1,682,850	255,933	1,938,783	22,272,462	36,297,712	36,297,712	1,150,426	164,401	9,921,768	15,917,946	4,437,935	386,265,928	27,651,887	23,794,670	7,125,006	4,370,237	35,289,913	63,638,244	17,562,499	1,119,142	82,319,884	440,018,840
4.850	3.650	2.500	0.000	95	101,503	1,641,746	255,933	1,897,679	22,272,462	36,297,712	36,297,712	1,138,922	162,757	9,822,552	15,926,012	4,440,184	390,085,859	28,076,655	23,844,141	7,165,693	4,370,237	35,380,070	63,770,552	17,662,788	1,119,142	82,552,482	442,968,375
4.900	3.600	2.500	0.000	95	101,503	1,577,097	256,086	1,833,183	22,272,462	36,297,712	36,297,712	1,120,601	160,139	9,664,544	15,938,858	4,474,518	391,872,641	28,145,102	23,856,293	7,177,331	4,370,237	35,403,861	63,803,052	17,691,475	1,119,142	82,613,670	444,131,003
4.950	3.550	2.500	0.000	95	101,503	1,518,509	257,188	1,775,697	22,272,462	36,297,712	36,297,712	1,103,980	157,764	9,521,204	15,950,511	4,508,994	393,643,519	28,250,271	23,868,842	7,189,163	4,370,237	35,428,242	63,836,617	17,720,640	1,119,142	82,676,398	445,323,980
5.000	3.500	2.500	0.000	95	101,503	1,443,621	258,332	1,701,953	22,272,462	36,297,712	36,297,712	1,082,235	154,656	9,333,667	15,965,758	4,544,976	395,516,867	28,390,230	23,881,792	7,201,189	4,370,237	35,453,218	63,871,251	17,750,282	1,119,142	82,740,675	446,569,083