Redesigning Highway Infrastructure Systems for Connected Autonomous Truck Lanes

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ABSTRACT

Previous studies on connected autonomous vehicles (CAVs) examined pavement performance and lane widths separately and in isolation, and without consideration for roadworks conditions. Hence, this study sort a holistic, optimal highway design solution for Connected Autonomous Trucks (CATs) by testing pavement failure and traffic performance under different cross-sectional configurations incorporating dedicated CAT lane, for both normal and temporary traffic management (TTM) arrangements. Firstly, a dual three-lane motorway (D3M) was selected as Base Case site. Next, previous research on sub-standard lanes were used to produce five non-standard cross-section alternatives, which were then modelled in 3D AutoCAD®. Capital investments to implement the alternatives were calculated by applying established industry construction cost models. Each cross-section was then subjected to different CATs penetration rates (PRs) and wheel wander regimes, and their pavement structural deterioration analysed using the Texas Mechanistic-Empirical Asphalt Concrete Pavement Design and Analysis System (TxME) software. From this, maintenance frequencies and costs were determined. The study estimated delays and delay costs during TTM, over a 20-year design period. Finally, initial investment, rehabilitation and delay costs were combined. It was found that the lowest life-cycle cost (LCC) of £19,091,470 occurred for high (80%) CAT PR operating under Standard D3M, while the highest LCC of £152,728,100 was also for high PR, but under Substandard D4M. Optimal LCC was found to change with different PRs. Hence cross-sections should be dynamically modifiable, given the anticipated gradual increase in PRs over time.

Keywords: Connected autonomous trucks, connected autonomous vehicles, cross-sections, pavement failure, highway infrastructure, maintenance cost, construction costs, lane widths, lifecycle costs (LCC), temporary traffic management, travel time cost.

INTRODUCTION

Background

Roads have a very important socio-economic impact in countries the world over. The UK economy particularly relies heavily on a properly functional highway network, as over 90% of goods are transported by road (MDS Transmodal 2019). The existing road infrastructure is worth £100 billion, and in 2020 the UK government committed to spending another £27.4 billion on projects for major road – including new corridors - over the next five years. (Department for Transport 2020a). 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. (Leech, Whelan et al. 2015), and the end of that decade witnessed well-supported forecasts about the imminence of completely driverless vehicles (Hummer 2020). Yet, the traditional highway engineering approaches have not adapted to these 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/CATs.

Motivation for study

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 (Elliott, McColl et al. 2003, Birth, Demgensky et al. 2011). 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 analyzed jointly, as their respective performances are mutually interdependent. [Shafiee, Nassiri et al. (2014), Siddharthan, Nasimifar et al. (2017)]. 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, with narrower lanes causing wheels to follow a narrow path, which causes a concentration in wheel load, while wider lanes have the opposite effect (Atkinson, Merrill et al. 2006). 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; but this could increase initial construction costs. Conversely, providing a narrow lane to take advantage of the close wheel tracking of CATs will reduce construction cost, but likely lead to premature pavement failure due to wheel load concentration from channelization. Furthermore, temporary roadworks conditions 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 remodeling highways for CATs assess performance, not only in times of normal operations, but also during temporary traffic management (TTM) for roadworks. (Bussey 2019). But 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 (Liu, Tight et al. 2019, Abdulsattar, Mostafizi et al. 2020, Adomah, Khoda Bakhshi et al. 2021, Pourfalatoun and Miller 2021).

Aims 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. This approach enabled the comparison of immediate, medium and long-term effects of various cross-section alternatives. The research used the following to derive monetary values for different performance outputs: industry-embedded construction costing methods; CAT wheel wander functions and their impacts on pavement failure; innovative, non-standard lane widths; existing traffic flow and speed models; economic values of time; and predictions for CAVs behaviour. The study allowed a comparison of different CAT PRs. The research focus was on rural motorways, because urban environments have increased complexities which will likely hinder connected autonomous driving.

LITERATURE REVIEW

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 analyze pavements and lane widths separately, and both groups typically excluding performance under roadworks conditions.

The first study to quantify the pavement failure effects of CATs established a link between the financial implications of CAVs and highway design. (Noorvand, Karnati et al. 2017). This was subsequently built on by other researchers (Chen, Song et al. 2019, Zhou, Hu et al. 2019a, Zhou, Hu et al. 2019b, Chen, Song et al. 2020, Gungor and Al-Qadi 2020a, Gungor and Al-Qadi 2020b). Collectively, they analyzed the impact of various CAV wander modes and PRs 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 minimize channelization, hence improving pavement longevity. These studies found pavement performance variances based on PRs. Particularly, under high PR, uniform wander delayed pavement failure, while zero wander caused early failure.

Studies on lane width requirements for autonomous driving usually only consist of undetailed, high-level reviews. (McDonald 2017, Paulsen 2018, Washburn 2018, Khoury, Amine et al. 2019).

Previous research on CAVs and work zones showed how autonomous vehicles can improve on safety and traffic flows (Adomah, Khoda Bakhshi et al. 2021). But, this only considered heterogenous traffic. Other research in this area focused on the use of CAVs as part of the temporary traffic management set up (Tang, Cheng et al. 2021), hence their findings do not apply to the public motorists. Yet another category of research regarding CAVs and work zones only provides insight into the technological system requirements (Park, Marks et al. 2016). These do not address the highway engineering elements associated with roadworks planning and installation.

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.

METHODOLOGY

To ensure all technical aspects are covered, this research applied the four-stage process for developing highway projects, namely Planning, Design, Construction and Maintenance. (Antillon, Garvin et al. 2018), as outlined below.

Stage 1 - Planning

The planning stage involved selecting a suitable site as a Base Case study that would facilitate the research purpose and scope. This led to the M3, a 95km dual carriageway motorway located in the southeast of England, UK. It runs in a southwest-northeast direction from London to Southampton as shown in Fig. 1. The M3 was chosen because:

- It is largely a rural motorway, so falls within the scope of this research
- It has a typical configuration (D3M), with three lanes and a hard shoulder for much of its length
- It is surrounded by sensitive ecology (ancient woodlands, national parks, conservation areas and protected species habitats), and would facilitate comparing environmental impacts of different alternatives.

The study excluded complex multi-vehicle interactions of CAVs and MVs at junctions (Zhu, Ma et al. 2022) by using a 3km length, the minimum distance between consecutive junctions that avoids merge/diverge maneouvres. (Department of Transport 1995). To ensure typical highway features were captured, a section was taken mid-way along the M3, located between Junctions 5 and 6 near Basingstoke, as shown in Fig. 2. This resulted in a 46.10m wide cross-section (between boundary fences) that is laterally symmetrical about the center of a 4.50m wide central reserve, with three standard traffic lanes 3.65m, 3.70m and 3.65m wide, respectively, and a 3.30m hardshoulder, all complying to current standards. (Highways England 2020a). Next to the hard shoulder is a 2.00m verge with filter drain and manholes, then a 2.00m high cutting with 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. The cross-section and highway features for this Base Case are represented in Fig. 3.

Stage 2 - Design

During this stage alternative highway cross-section scenarios were modelled using 3D AutoCAD®, an engineering software that increased design efficiency and accurate quantities measurements for cost estimates. The range of alternatives was based on the "Do-nothing"- "Do-minimum"- "Do-something" options appraisals for transport projects which relate to how extensively the Base Case is modified.(Department for Transport 2011). All alternatives incorporated a dedicated CAT lane, as this has shown to provide the best operational performance. (National Cooperative Highway Research Program (NCHRP) 2018). Because early CAV adoption is expected to be for heavy trucks (Hummer 2020), lighter vehicles were analysed as having no or only partial autonomy. Existing research on reduced lane widths for motorways (Kondyli, Hale et al. 2019), coupled with industry guidance for using narrow lanes for temporary traffic management (Gregg 2007), were used to produce sub-standard, but feasible, lane widths. Also, innovative cross-section solutions were developed purposefully for this research, allowing the special wheel tracking capabilities (uniform and zero-wheel wander) of CATs to be accounted for. In all five cross-section alternatives were produced, as described subsequently.

Cross-section Alternative 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, see Fig. 4. All physical features are retained, hence no construction costs incurred.

Cross-section Alternative 2: Substandard D3M

As with Option 1, no carriageway widening is undertaken for alternative 2. The three lanes are also retained, but are re-configured so that the dedicated CAT lane is 5.00m wide, which is above standard to enable CAT uniform wheel wander to spread wheel loads over a wider area. Substandard lanes of 3.25m (middle lane) and 2.75m (innermost lane) are provided for manual trucks and for passenger cars/vans, respectively. Fig. 5 shows the details of this option. The construction cost incurred relate to relocating road markings and road studs.

Cross-section Alternative 3: Substandard D4M

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 lanes of 3.15m width for manual trucks is also provided, alongside two substandard 2.50m width car lanes/vans. This produced a substandard four-lane (D4M) section as shown in see Fig. 6. Construction works cost will involve removing and re-installing road marking and road studs on the carriageway to the new cross-section.

Cross-section Alternative 4: Standard D4M

This option involves widening to provide an extra lane, with all four lanes being to standard. The widening will require full-depth pavement construction, removal and rebuilding of underground items including drainage and utilities, earthworks to move the cutting, removal and re-planting of trees and other vegetation, and acquisition of extra land from third parties. This scenario, depicted in Fig. 7, is to enable comparison of operational benefits from extra lane against the associated increased construction costs.

Cross-section Alternative 5: Above-standard D4M

This option is similar to Cross-section Alternative 4, but the additional CAT lane provided is 5.00m wide, which is wider than the standard of 3.65m, see Fig. 8. Three standard lanes are provided for all MVs. Construction works will be more extensive versions of the items covered in Alternative 4. Alternative 5 will determine if improved pavement performance of extra-wide CAT lane justifies the high cost of major reconstruction to existing motorways.

To conclude, all alternatives are non-standard, as provision of dedicated (CAT) lanes on motorways is not permitted (alternatives 2, 3 and 5 also contain substandard and/or above-standard widths) (Highways England 2020a). They are, therefore, Departures from Standards, and consequently require pre-implementation approval (McCullagh 2016).

Stage 3 - Construction

The third stage of the methodology was determining the initial capital investment required to construct the engineering alternatives. This involved applying well-established industry practice and data. In general, total highway project costs consists of: (i) 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). For this study, Highways England’s library of works items was analyzed (Table 1). (Department for Transport). This approach eliminated the risk of inadvertently omitting any works items, preserving the holistic remit of the study. Analysis was then undertaken to determine whether - and how – the individual work items will be impacted when the existing Base Case Cross-section is remodeled to produce the five cross-section alternatives. Each work item was categorized as one of the following:

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

Table 1 contains the analysis results. This shows that the below civil engineering works cost items will be impacted:

- Preliminaries
- Site Clearance
- Fencing
- Drainage and Service Ducts
- Earthworks
- Pavements
- Traffic signs and road markings
- Accommodation works and Statutory Undertakers
- Landscape and Ecology

Once the affected items were identified, their quantities were calculated using the First Principles (or Bottom-Up) approach (Infrastructure and Projects Authority 2021). This facilitated the quantification of individual items, thus enabling the comparison of different cross-section alternatives at a granular level, so even minor differences were detectable. Measurements were taken from the AutoCAD models using in-built software functions, and 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). Preliminaries, Statutory Undertakers and Land-take costs were determined by using typical cost distributions among various items from historic road project cost i (Department for Transport 2007). This research is deemed commensurate with feasibility design stage, therefore, a 44% Optimism Bias was applied. (Mott MacDonald 2002).

Stage 4: Maintenance during operational phase

The fourth and final stage involved maintenance, which entailed two parts: a) actual works costs to renew the pavement structure and b) travel delay due to these rehabilitation works.

a) Pavement renewal costs and frequency

Pavement deterioration rates for each scenario was determined using Texas Mechanistic-Empirical Asphalt Concrete Pavement Design and Analysis System (TxME) software, 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, Zhou et al. 2013). For this study the analysis was performed using a 360mm three-layer dense-graded asphalt concrete pavement laid on 200mm of granular sub-base on a 15% California Bearing Ratio (CBR) sub-grade strength which was converted to equivalent modulus of 14.5ksi (Highways England 2020b). The pavement structure is shown in Fig. 10. CAT PRs of 20%, 50% and 80%, representing low, medium and high penetrations, respectively were used. Wandering standard deviations of 3in (75mm), 10in (250mm), and 40in (1000mm) were assessed to measure effects of different wheel lateral movements for CATs (Zhou, Hu et al. 2019a, Zhou, Hu et al. 2019b), while manual trucks were modeled using a normal wander distribution with a 10in standard deviation. To calculate the Equivalent Single Axle Loads (ESAL) for the TxME analysis, historical UK motorway traffic data was extracted (Department for Transport 2020b). Base traffic volumes and HGV content were determined from 2019 traffic figures (Department for Transport 2021), so as to filter out the impact of COVID on traffic flows. This ensured the results represent long-term traffic trends. Linear interpolation was used to obtain annual traffic growth rates from available government sources (Department for Transport 2018a). 2025 was then selected as the project opening year, as this is when fully autonomous vehicles are predicted to be introduced (KPMG International 2019). A 20-year design period was used, in accordance with pavement assessment criterion for existing roads. The results of the design traffic data analysis are shown in Table 2. The Total ESAL over the design period was then derived from equation (1) (Highways England 2020b).

$$ESAL = 365 \cdot \mathrm{P} \cdot \mathrm{D} \cdot 10^{-6} \cdot \sum_{i=1}^{n} Fi \tag{1}$$

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 (Highways England 2020b), see Fig. 9.

F_i = Average daily HGV flow for the i^{th} year of the project opening

n = Design period in years, taken as 20

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

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 (Highways England 2020b), thus:

$$CAT_{MD} = 89 - (0.0014 \cdot CAT_M) \tag{2}$$

where CAT_{MD} is the ESAL for manual trucks in the heaviest loaded, and CAT_M is the total ESAL for manual trucks.

The ESALs for CATs and manual trucks for the different CAT penetration rates are shown in Table 3.

Propagation of cracking damage and rut depth over time was then collated from the TxME results, from which maintenance frequency was calculated. Cost estimation methods similar to those described above for initial capital investment budgets were then used to calculate costs for removing and replacing the layers of damaged pavement.

b) Travel delay during pavement rehabilitation

The study considered two pavement rehabilitation cases: CAT and manual truck lane rehabilitations. Lighter vehicles were discounted as they impose negligible pavement damage. Designs for temporary cross-sections and layouts during pavement rehabilitation works were then undertaken using AutoCAD, as was done for normal operations designs. 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. 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, Leal Ruiz et al. 2021). All the TTM options used lane closures and narrow lanes, with no road closures/diversions. The results of the TTM designs are illustrated from Fig. 11-Fig. 15. Time delays experienced each day during TTM were then calculated from traffic flow models relating speeds to lane widths (Chitturi and Benekohal 2005), and speeds to flow volumes (Horowitz 2009). To determine the total delay, the total duration (or number of days) that TTM was in place had to be calculated, and this was achieved by applying the Bromilow time-cost (BTC) model (Kaka and Price 1991), which is a linear regression relationship of the form:

$$T = k \cdot C^{B} \quad (3)$$

Where:

T is the construction time (in working days)

C is the construction value (in £m), in this case the total project cost of the rehabilitation works

k and B are constant coefficients. For major highway projects, k = 258.1 and B = 0.469.

Value of time information from Department for Transport (DfT) were then used to establish the cost of delays, (Department for Transport 2018b). Finally, a Discount rate of 3.5% was applied to each of the annual delay costs, to obtain a Present Value (Treasury 2020).

RESULTS, ANALYSIS AND DISCUSSION

A sample of the construction works items cost estimates calculation is shown in Table 4, and is based on cross-section alternative 4. Table 5 presents the initial capital investment costs for all the alternative cross-sections, showing that if widening is not implemented, then Substandard D3M (Alternative 3) produces the highest initial cost of £148,000. Unsurprisingly, the two widening options - Standard D4M (Alternative 4) and Above-standard D4M (Alternative 5) - produced the highest initial costs, which were relatively similar at £58.8m and £62m, respectively.

The TxME software analysis results for rutting and fatigue cracking failure are plotted in Fig. 16 and Fig. 17, respectively. Rut depth failure threshold was taken at 10mm (0.4in), while the fatigue cracking failure threshold was taken at 1% of wheel track width (Highways England 2020b). At these threshold points pavement rehabilitation is undertaken to restore serviceability. In all cases, the pavement reached rutting failure before the cracking threshold was reached. The results of this analysis are shown in Table 6. 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. For the manual truck lane, failure was almost exclusively dependent on the CAT proportion as this is what directly affected the volume of manual trucks. The costs of removing defective pavement layers and replacing these with new ones each time are shown in Table 7, which also contains the travel delay costs. As expected, wider lanes incur higher single rehabilitation costs due to increased quantities of works cost items, coupled with increased construction times, which increases time-related construction costs (Preliminaries, Preparation, Design and Supervision costs).

Finally, the initial investment cost for each cross-section alternative (Table 5) is added to the corresponding TTM travel delay cost (Table 8), and the combined cost obtained is represented in Fig. 18. From this information, it is clear that at low penetrations of 20%, Substandard D4M produces the most cost-effective solution for implementing CATs, as the life-cycle cost is three times less than the widening options (Standard D4M and Above-standard D4M) and approximately 50% lower than the other non-widening options (Standard D3M and Substandard D3M). However, at high penetration rate of 80%, the Substandard D4M becomes prohibitively expensively. This is due to frequent failure of the narrow lane, leading to frequent maintenance, with its associated traffic interruptions and increased travel delays. However, if only maintenance/operational cost is being considered, then Above-standard D4M produced the lowest rehabilitation and travel delay cost. This is attributable to reduced maintenance frequency on the wide (5m) CAT lane as it is subjected to fewer loading. Among the three non-widening options, cross-section Substandard D4M under low CAT PR (20%) presents the best case for travel delay cost during TTM, closely followed by Standard D3M under high (80%) CAT PR.

CONCLUSIONS

This study outlined approach for designing and assessing five innovative motorway cross-sections that utilize the wheel wander capabilities of autonomous vehicles under dedicated CAT lane arrangement. All the cross-sections are non-standard, and would require assessment and approval by National Highways through their Departures from Standards processes, prior to implementation. The paper outlines how AutoCAD was used to produce the different cross-sections under both normal and temporary traffic management situations, and to measure quantities accurately, which were then combined with secondary pricing data and costing models to calculate initial investment and maintenance construction costs. Using a 360mm thick asphalt concrete pavement, maintenance frequencies were determined using TxME software. Traffic flow models and speed-lane width relationships, as well as value of time data, were then used to calculate delay costs for different during TTM conditions. The results showed that:

- The initial construction costs ranged from £0 for 'Do-nothing' solution, where the existing standard D3M is retained, to £62m for a 'Do-something' option of Above-standard D4M incorporating a 5m wide CAT lane.
- Above-standard D4M at 20% penetration produced the lowest travel delay cost of £6,680,612, while Substandard D4M at 80% penetration produced the highest travel delay cost of £152,580,417.
- At 50% penetration, Standard D3M resulted in the lowest LCC among the five cross-section alternatives.
- Overall, the lowest life-cycle cost of £19,091,470 was obtained at high (80%) CAT PR under Standard D3M, while the highest LCC of £152,728,100 was also for high CAT PR, but under Substandard D4M.

These values demonstrate that the cross-section solution that minimises delays under temporary works condition is Above-standard D4M. But this solution may not be financially favorable (or even feasible) as it incurs the highest upfront construction cost. In summary, the results demonstrate that adapting existing highways for CATs, and CAVs in general, may have to be done dynamically, where cross-sections are modified based on prevailing penetration rates. This will require highway cross-section to be designed such that they can be easily adapted over time.

PRACTICAL APPLICATIONS AND ADDITIONAL RESEARCH

Current DMRB design standards for pavements and geometry do not account for CAVs. In order to standardize the analysis of pavement design subjected to CAT loading, other pavement structures (different flexible pavement thicknesses, as well as composite and rigid pavement systems) should be investigated. The results 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. 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 paper can support Departure from Standards applications to National Highways for using innovative solutions to accommodate CATs. That said, this research will benefit by expanding the alternatives to include a dedicated offside CAT lane, as only nearside CAT lane was considered. Incorporating accidents and environmental indices in the analysis will ensure non-engineering factors are also considered. Also, the case study site should be extended in further work to a more complex road network, to simulate realistic traffic interactions. Technology infrastructure for CAVs, which can impact significantly on highway engineering designs, was outside the scope of this paper, but can be included in future studies.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

- Construction cost estimates
- Traffic data and prediction models
- Travel delay under temporary traffic management conditions

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: H. Jehanfo, I. Kaparias, J. Preston, A. Stevens. data generation: H. Jehanfo, S. Hu and F. Zhou; analysis and interpretation of results: H. Jehanfo, S. Hu and F. Zhou; draft manuscript preparation: H. Jehanfo. All authors reviewed the results and approved the final version of the manuscript.

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545 **TABLES**

546 **Table 1.** Scoping out elements for calculating base construction costs for initial capital investment

SERIES	WORKS ITEM DESCRIPTION	IN SCOPE?	REASON
100	**Preliminaries**	**Yes**	**Construction duration differs by scenario, hence time-related will be affected**
200	**Site Clearance**	**Yes**	**Lane widths affect project footprint, and thus, the area of site clearance**
300	**Fencing**	**Yes**	**Fencing would require relocating, depending on the cross-section alternative**
400	Road Restraints Systems	No	CATs will impact safety, but this is out of scope. No nearside barrier in the Base Case, and the offside barrier is unaffected.
500	**Drainage and Service Ducts**	**Yes**	**Existing verge drainage will need relocating, depending on scenario**
600	**Earthworks**	**Yes**	**Excavation for new pavement construction and new slopes for widening**
700	**Pavements**	**Yes**	**Lane and carriageway widths differ among scenarios**
800	Road Pavements - Unbound, Cement and Other Hydraulically Bound Mixtures	No	Included in 700 above
900	Road Pavements - Bituminous Bound Materials	No	Included in 700 above
1000	Road Pavements - Concrete Materials	No	Included in 700 above
1100	Curbs, footways, and paved areas	No	Curb-less, over-the-edge pavement is used in all alternative cross-sections. No footway along the M3. All alternative cross-sections exclude extra paved areas beyond the carriageway
1200	**Traffic signs and road markings**	**No**	**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 this research as it relates to technology. The 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, Works for Statutory Undertakers, Provisional Sums and Prime Cost Items**	**Yes**	**A utilities investigation showed that there is an existing gas pipeline on along the M3. Allowance to also be made for accommodation works and other statutory undertaker assets (Department for Transport 2007)**
3000	**Landscape and Ecology**	**Yes**	**Replanting of trees on cutting slope**
5000	Maintenance Painting of Steelwork	No	Mainly determined by environmental factors

Bold rows of text to emphasize works items impacted by CAT introduction and included in construction cost calculations

Table 2. 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
DESIGN PERIOD	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	25.92	104,891	10.0	8.84	10,517
	2042	19.44	99,494	10.6	9.38	10,569
	2043	12.96	94,096	11.3	9.92	10,621
	2044	6.48	88,698	12.0	10.46	10,674

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

Table 3. Summary of ESALs loadings for CATs and manual trucks used in TxME analysis

CAVs Ratio (%)	**0**	**20**	**50**	**80**	**100**
Loading in CATs Lane (ESALs)	0	26.4	66	105.6	132
Loading in Manual Lane (ESALs)	117	94	59	23.5	0

Table 4. Works Items Cost Estimate for Cross-section Alternative 4 (Minor Carriageway widening)

ITEM AND DESCRIPTION	UNIT	QUANTITY	RATE (£)	COST (£)	REMARKS
SITE CLEARANCE					
General site clearance (medium density wooded)	m^2	73,200	0.44	32,208	Width is from cross-section. Study section length is 3km. Manhole spacings designed using industry guidance (Water UK 2021)
Take up or down and remove to store off site - Chamber cover and frame	No.	210	5.14	1,079	
Take up or down and remove to tip off site-Timber post and 4 rail fence.	m	6,000	17.3	103,800	
Take up or down and remove to tip off site-road studs	m	17,724	0.29	5,140	
SITE CLEARANCE SUB-TOTAL				***142,557***	
FENCING					
Timber rail fencing - 1.4 m high, timber posts and four rails	m	6,000	27.75	166,500	
DRAINAGE					
Entire drainage run elements, including pipe and trenching materials, chambers, manholes and excavations	m	6,000	234.72	1,408,329	
EARTHWORKS					
Motorway cutting in acceptable material	m^3	19,951.03	16.48	328,793	
Disposal of unacceptable material to tip within 1km	m^3	124,31.92	4.51	56,068	
Disposal of unacceptable material over 1km	m^3	124,31.92	2.26	280,963	Based on a 10km tip distance
Compaction of granular fill material	m^3	4,440	3.42	15,185	
EARTHWORKS SUB-TOTAL				***681,009***	
PAVEMENTS					
200mm thick Granular Sub-base	m^2	22,200	43.88	974,136	Rates have been interpolated/extrapolated where items are not available
Surface Course 40mm thick	m^2	22,200	12.98	288,045	
Binder Course 100mm thick	m^2	22,200	21.28	472,416	
Base 220mm thick	m^2	22,200	39.63	879,881	
PAVEMENTS SUB-TOTAL				***2,614,478***	
TRAFFIC SIGNS AND ROAD MARKINGS					
Reflectorized white line; 200 mm wide	m		1.85	33,300	
Cat-eye reflector road studs	m		1.03	18,620	
TRAFFIC SIGNS AND ROAD MARKINGS SUB-TOTAL				***51,920***	
LANDSCAPING AND ECOLOGY					
All landscaping including ground preparation, grass seeding, tree planting and tree protection	m^2	39,000	435.1	16,968,935	Existing tree spacings based on likely prevailing highway landscaping guidance during M3 construction.(Way 1976)
TOTAL OF WORK ITEMS					**£22,033,728**

Table 5. Initial capital investment costs

Cross section Alternative	DIRECTLY MEASURED WORKS ITEMS (£m)							DERIVED ITEMS (£m)				TOTAL (£m)	TOTAL INLCLUDING 44% OPTIMISM BIAS (£m)
	Site Clearance	Fencing	Drainage	Earthworks	Pavements	Traffic Signs and Road Markings	Landscaping and ecology	Preliminaries (42.6% of works items)	Accommodation Works & Statutory Undertakers (13% of works items)	Land-take (13% of works items)	Design and Supervision (16.7% of works items)		
Alt. 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Alt. 2	0.003	0.000	0.000	0.000	0.000	0.035	0.000	0.016	0.004	0.004	0.006	0.070	**0.102**
Alt. 3	0.003	0.000	0.000	0.000	0.000	0.052	0.000	0.024	0.007	0.007	0.009	0.103	**0.148**
Alt. 4	0.143	0.167	1.408	0.681	2.614	0.052	16.969	9.386	2.864	2.864	3.680	40.828	**58.793**
Alt. 5	0.146	0.167	1.408	0.918	3.568	0.052	16.969	9.895	3.020	3.020	3.879	43.041	**61.979**

Table 6. Structural life of pavement under different penetration rates and lane widths

CAT Penetration, %	ESALs	Standard Deviation	Lane Width, in m	Rut Life @ 10mm (0.4 inches), in months
CAT lane, based on uniform distribution wander model				
20	26.4	76mm (3 in)	2.85	50
50	66	76mm (3 in)	2.85	14
80	105.6	76mm (3 in)	2.85	13
100	132	76mm (3 in)	2.85	12
20	26.4	254mm (10 in)	3.65	74
50	66	254mm (10 in)	3.65	26
80	105.6	254mm (10 in)	3.65	14
100	132	254mm (10 in)	3.65	14
20	26.4	1016mm (40 in)	5.00	254
50	66	1016mm (40 in)	5.00	121
80	105.6	1016mm (40 in)	5.00	74
100	132	1016mm (40 in)	5.00	62
Manual trucks lane, based on normal distribution wander model				
80	23.5	254mm (10 in)	3.70	102
50	59	254mm (10 in)	3.70	39
20	94	254mm (10 in)	3.70	27
0	117	254mm (10 in)	3.70	19

Table 7. Cost of single removal and replacement of defective pavements

Cross-section Alternative	CAT lane rehabilitation Cost (£)	Manual lane rehabilitation cost (£)
1 - Standard D3M	409,692	415,304
2 – Substandard D3M	561,222	364,794
3 – Substandard D4M	319,896	353,570
4 – Standard D4M	409,692	415,304
5 – Above-standard D4M	561,222	415,304

Table 8. Pavement rehabilitation frequency and travel time/delay cost during TTM

CAT %	Pavement Rehabilitation Freq (every …years)		Delay cost to vehicles each time CAT lane is closed for Rehabilitation (£)			Delay cost to vehicles each time Manual Truck Lane is closed for rehabilitation (£)			Total discounted cost over pavement design life (£)
	CAT Lane	Manual Trucks Lane	CAT	Manual Trucks	Passenger Cars	CAT	Manual Trucks	Passenger Cars	
Cross-section Alternative 1									
20	9.1	2.25	176,737	293,482	888,929	177,868	268,247	3,200,271	27,897,071
50	4	3.25	441,842	183,426	888,929	444,670	167,654	3,200,271	24,182,802
80	2.16	8.5	706,947	73,371	888,929	711,472	67,062	3,200,271	19,091,470
Cross-section Alternative 2									
20	21	2.25	204,846	988,465	4,095,326	66,949	807,639	3,346,145	31,894,583
50	10	3.25	512,116	910,428	6,002,978	418,432	157,762	4,904,820	34,143,098
80	6.16	8.5	819,386	528,048	8,673,691	267,796	431,450	7,086,965	32,040,828
Cross-section Alternative 3									
20	4.16	2.25	157,374	111,911	508,241	65,975	795,888	2,255,830	18,981,530
50	1.16	3.25	393,436	69,944	508,241	164,937	733,055	5,081,810	83,355,778
80	1.1	8.5	629,497	27,978	508,241	263,900	425,172	9,153,514	152,580,417
Cross-section Alternative 4									
20	9.1	2.25	176,737	125,679	1,191,154	71,147	309,191	933,566	8,634,415
50	4	3.25	441,842	78,550	1,191,154	177,868	193,244	1,434,759	15,283,740
80	2.16	8.5							29,853,521
Cross-section Alternative 5									
20	20	2.25	204,846	145,669	1,380,606	71,147	309,191	1,000,481	6,680,612
50	10.1	3.25	512,116	91,043	1,380,606	177,868	193,244	1,537,598	8,239,274
80	6.16	8.5	819,386	36,417	1,380,606	284,589	77,298	1,916,792	10,518,221

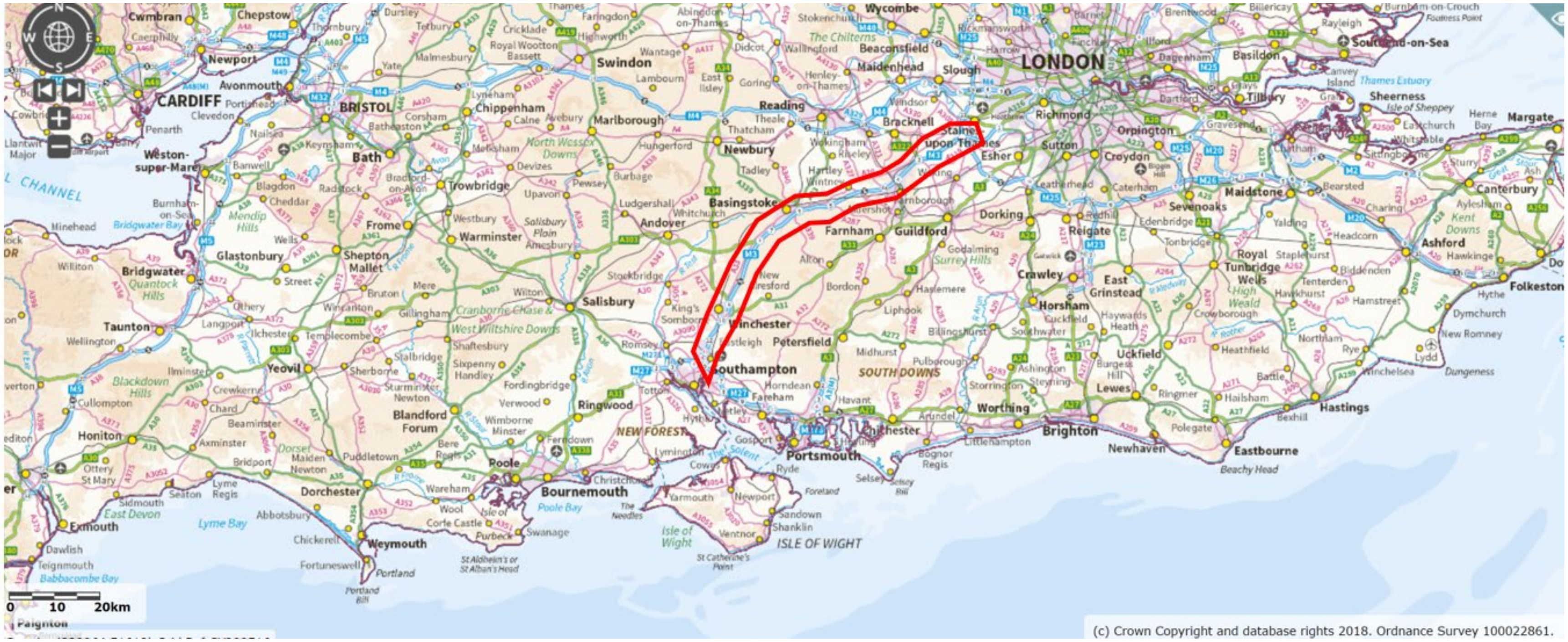


Fig. 1. M3 Motorway location

Fig. 2. Base Case physical features

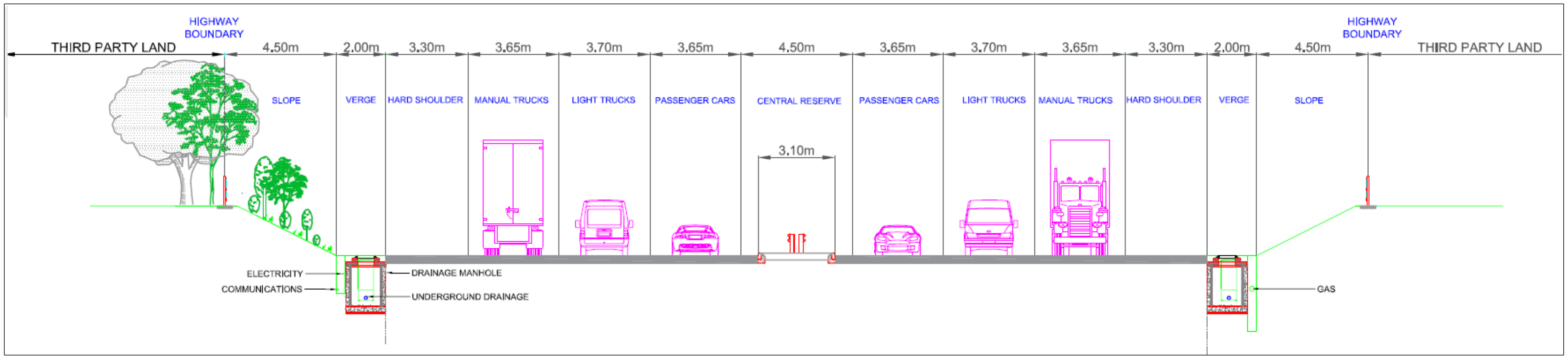


Fig. 3. Base case geometric engineering features

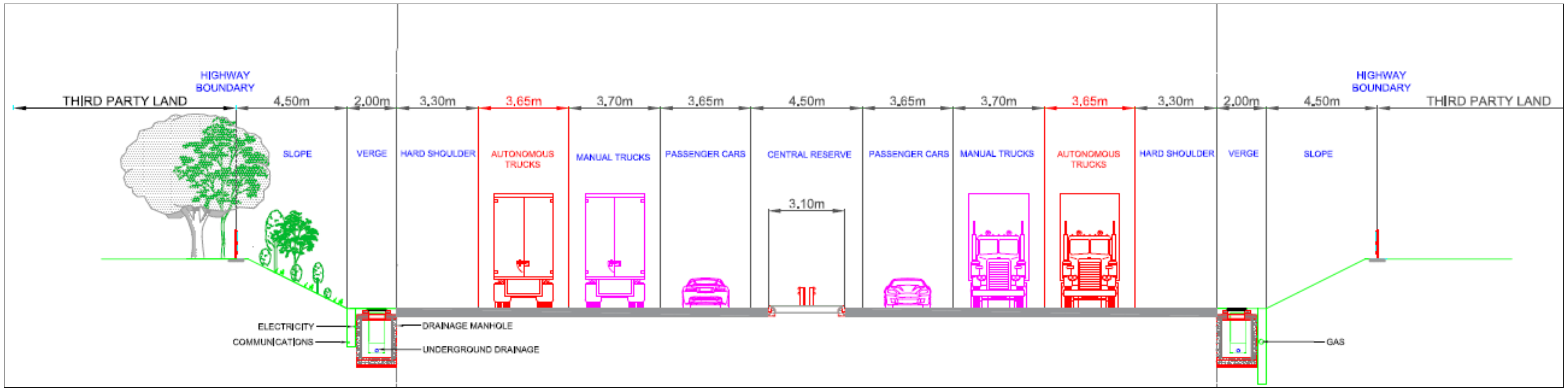


Fig. 4. Cross-section Alternative 1: Standard D3M

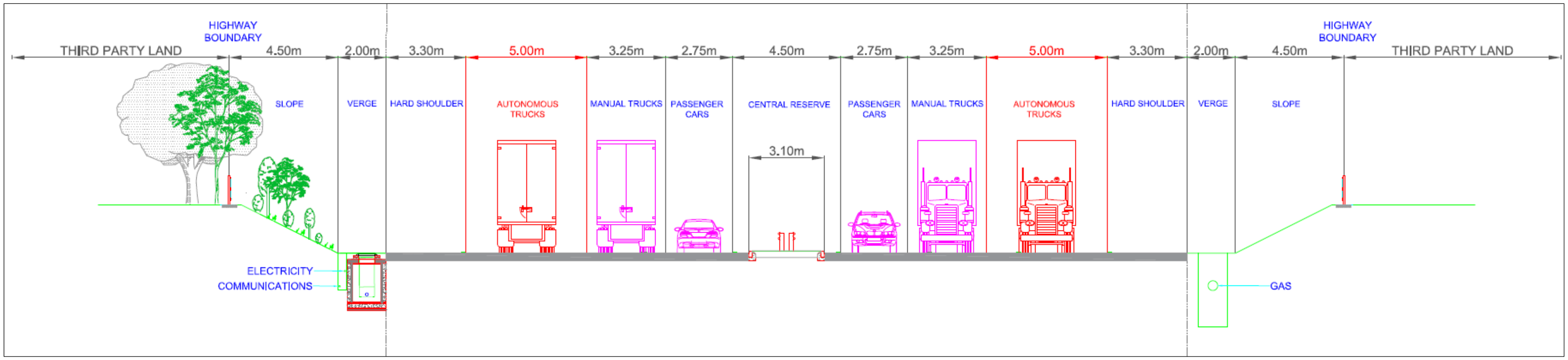


Fig. 5. Cross-section Alternative 2: Substandard D3M

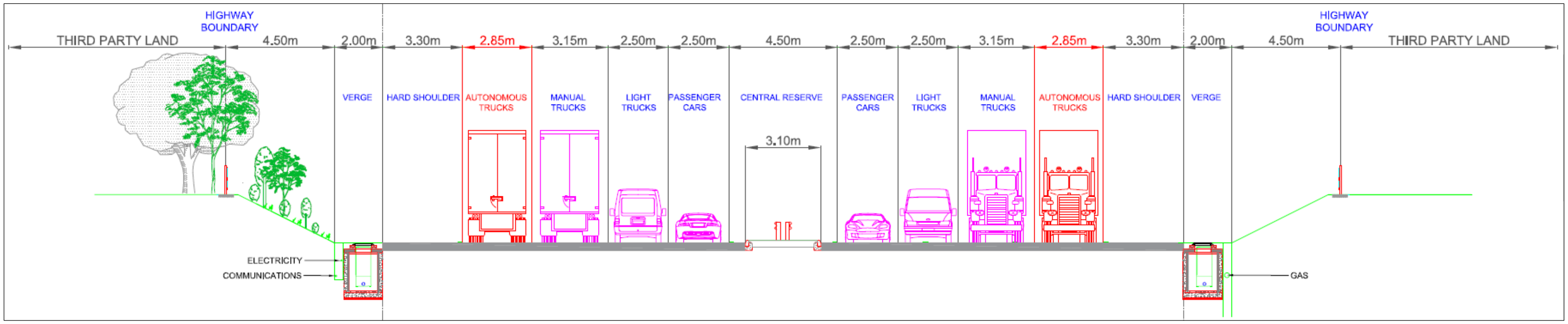


Fig. 6. Cross-section Alternative 3: Substandard D4M

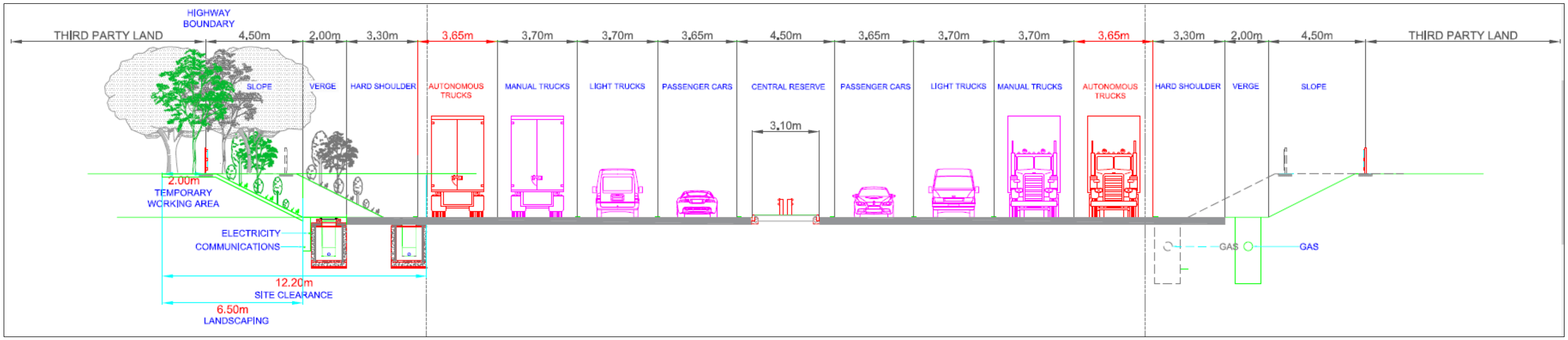


Fig. 7. Cross-section Alternative 4: Standard D4M

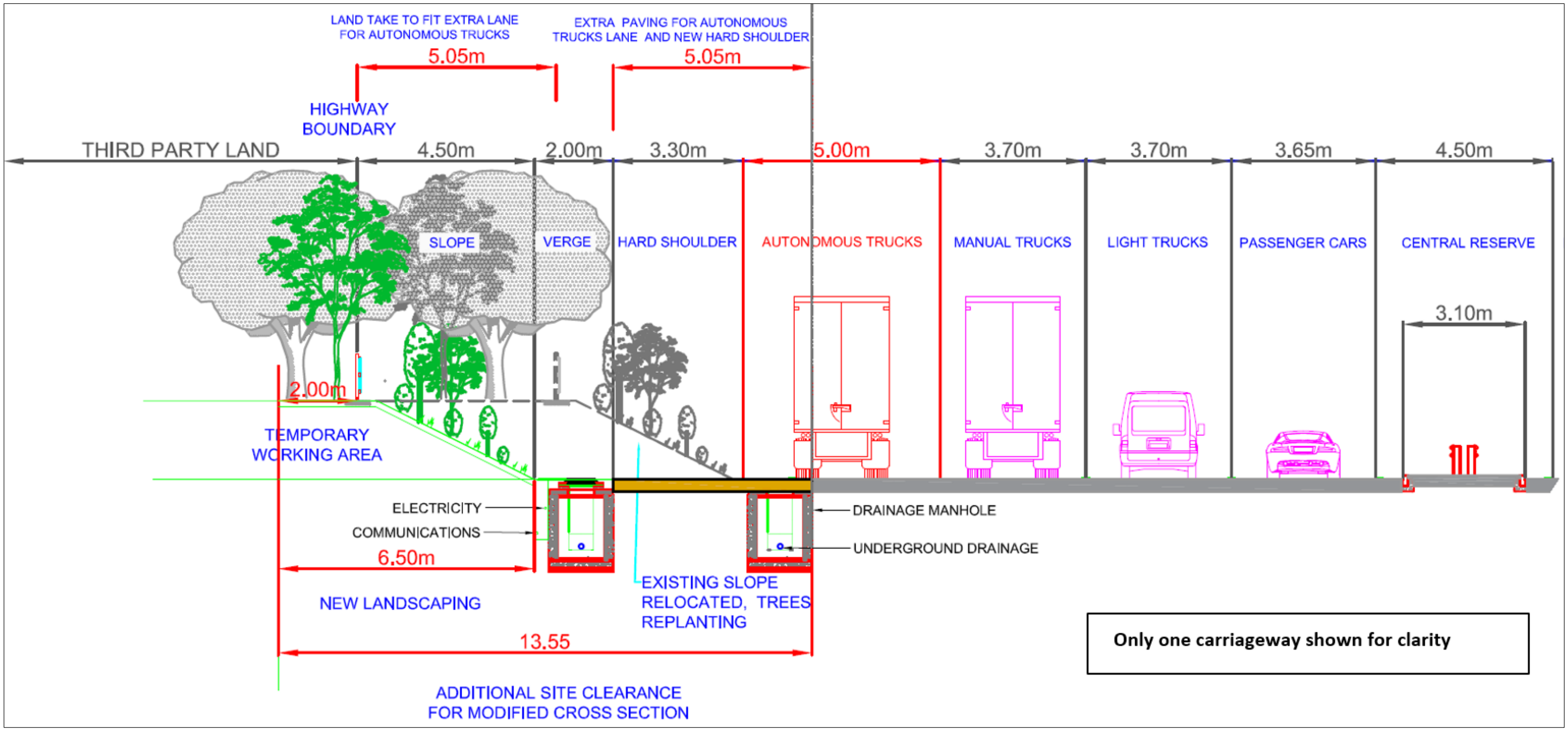


Fig. 8. Cross-section Alternative 5: Above-standard D4M

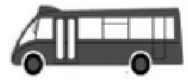
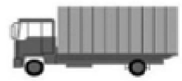
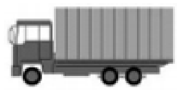
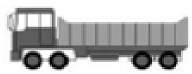
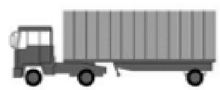
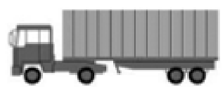
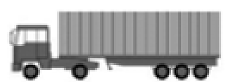
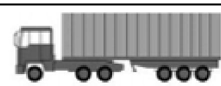
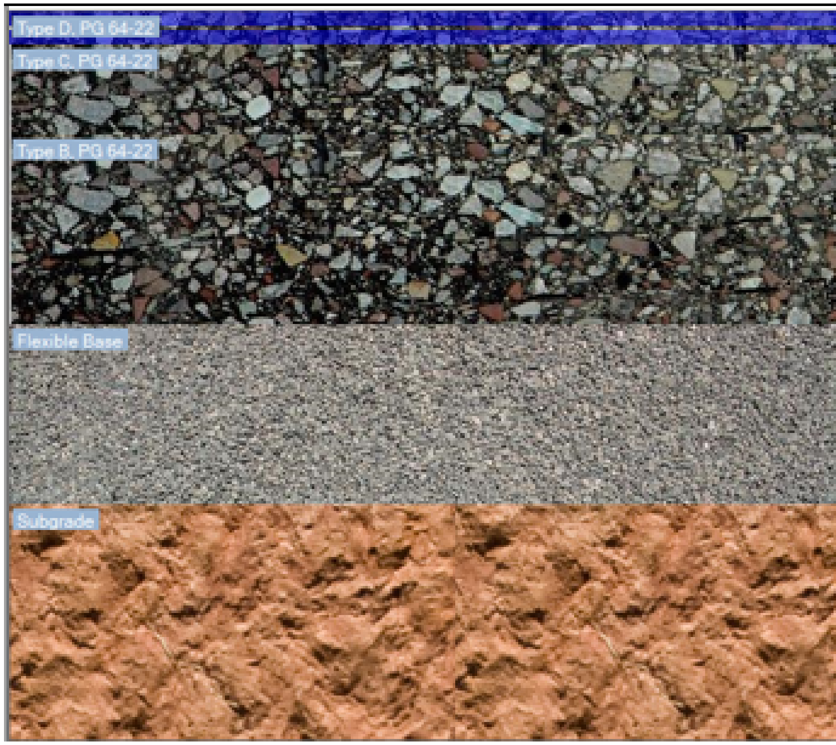
Vehicle Category	Damage Factor
 Buses and Coaches	3.9
 2-axle rigid	0.6
 3-axle rigid	3.4
 4-axle rigid	4.6
  3 and 4-axle articulated	2.5
 5-axle articulated	4.4
 6-axle articulated	5.6
Average Damage Factor	**3.57**

Fig. 9. Determination of Average Damage Factor



40mm (1.5in) Surface course
100mm (4 in) Binder course
220mm (8.5in) Base course
200mm (8in) Granular Base, modulus 22ksi
Sub-grade, modulus 14.5ksi

Fig. 10. Pavement structure for analysis

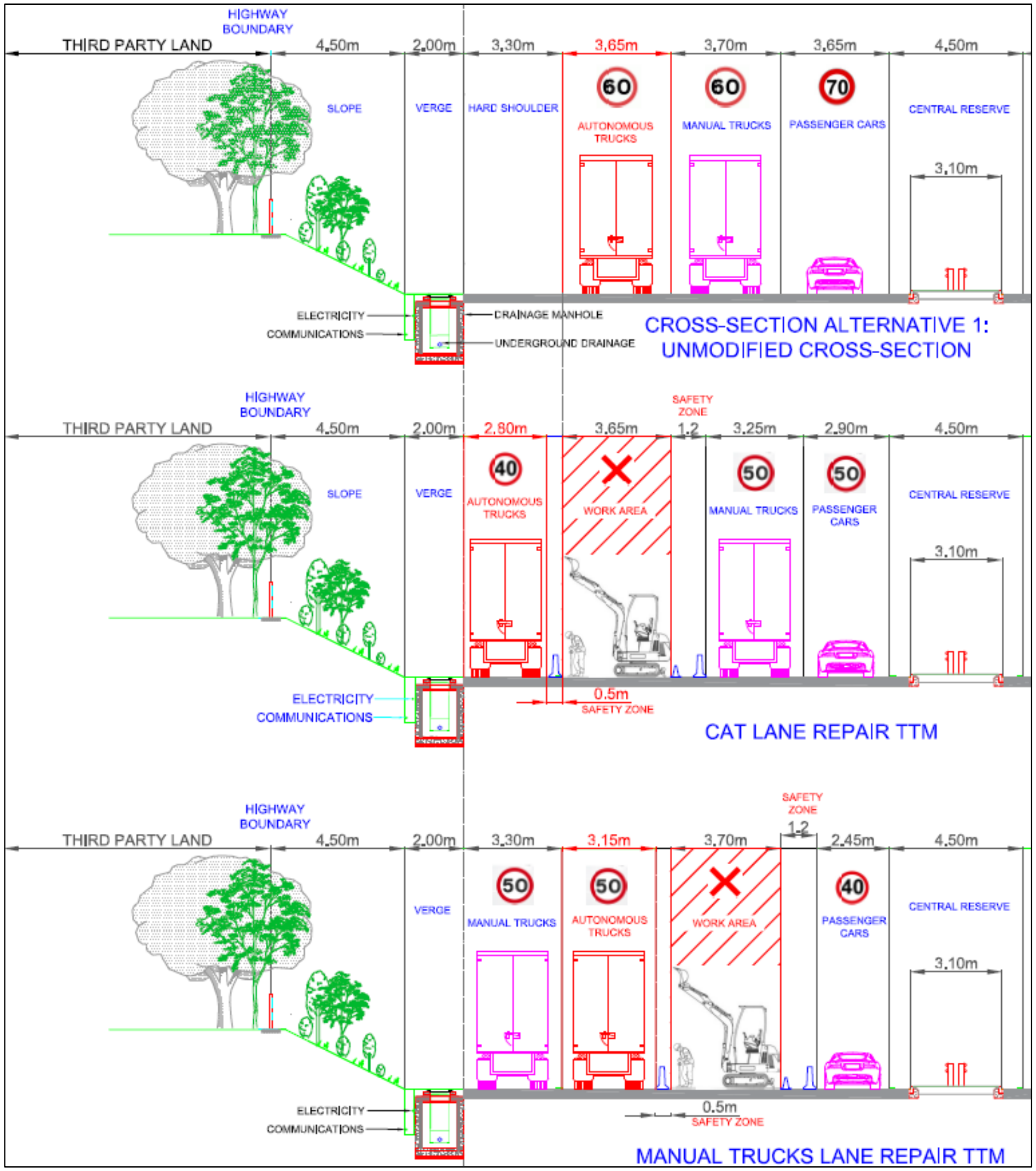


Fig. 11. Standard D3M – permanent and TTM conditions

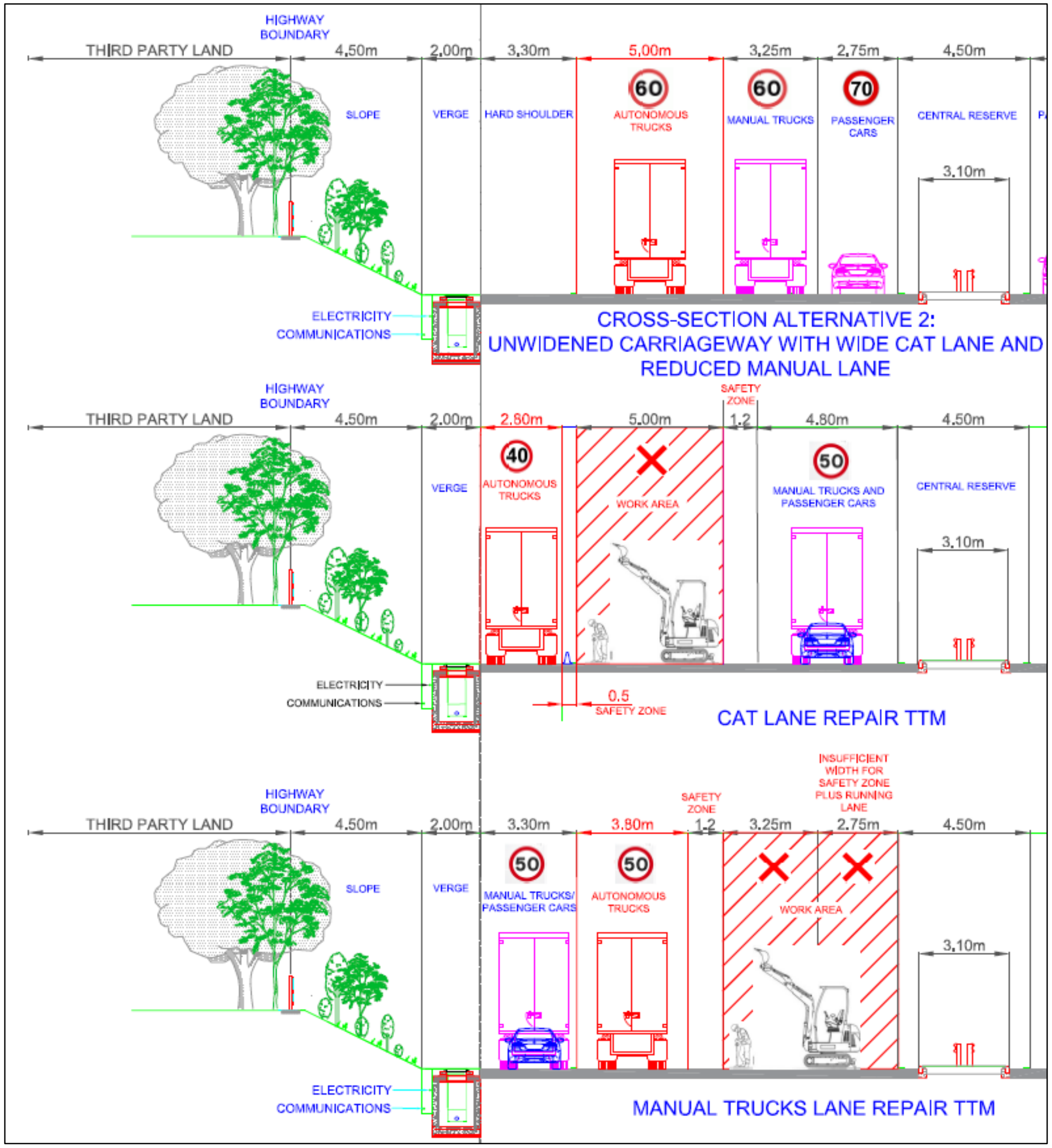


Fig. 12. Substandard D3M – permanent and TTM conditions

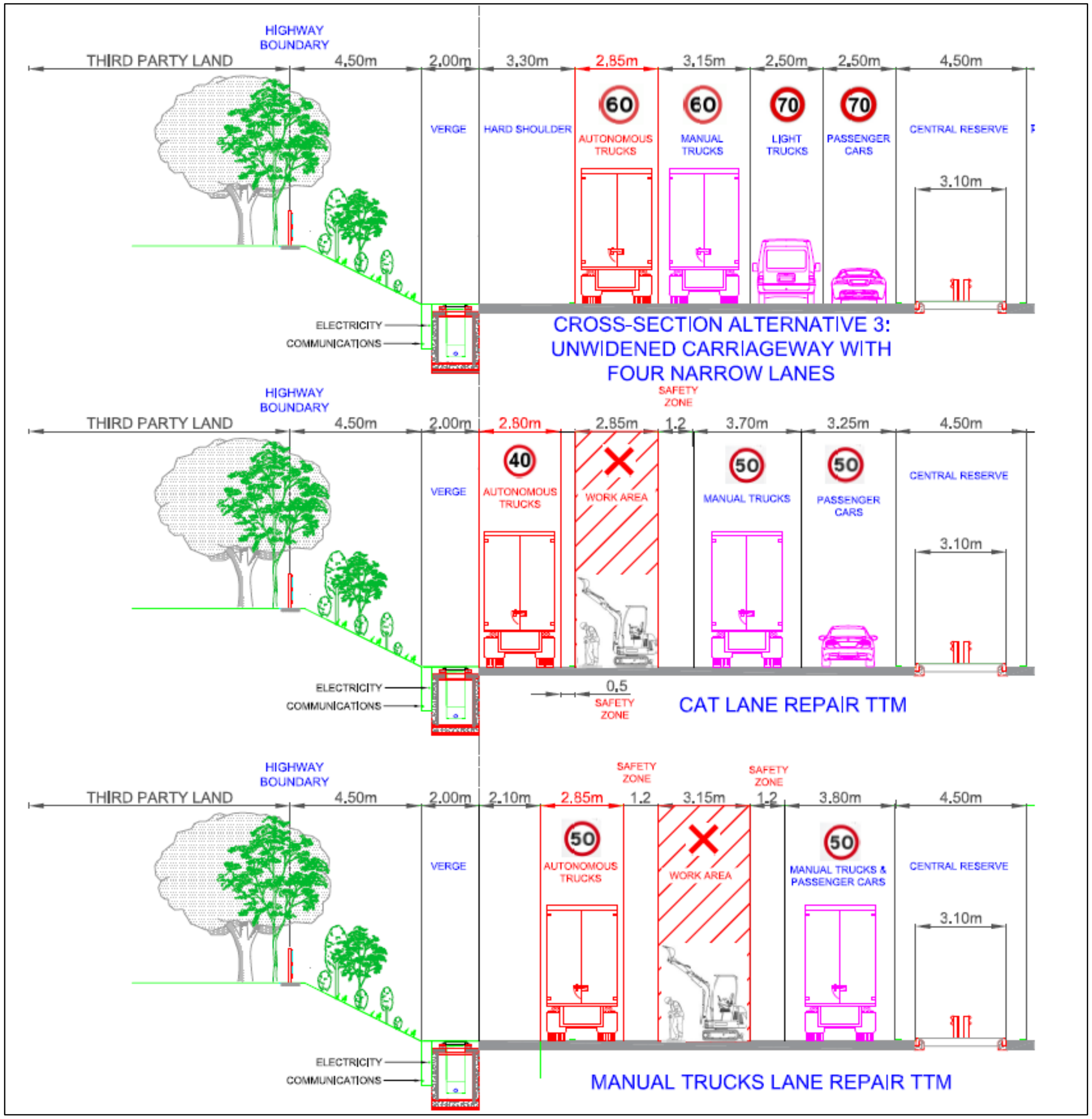


Fig. 13. Substandard D4M – permanent and TTM conditions

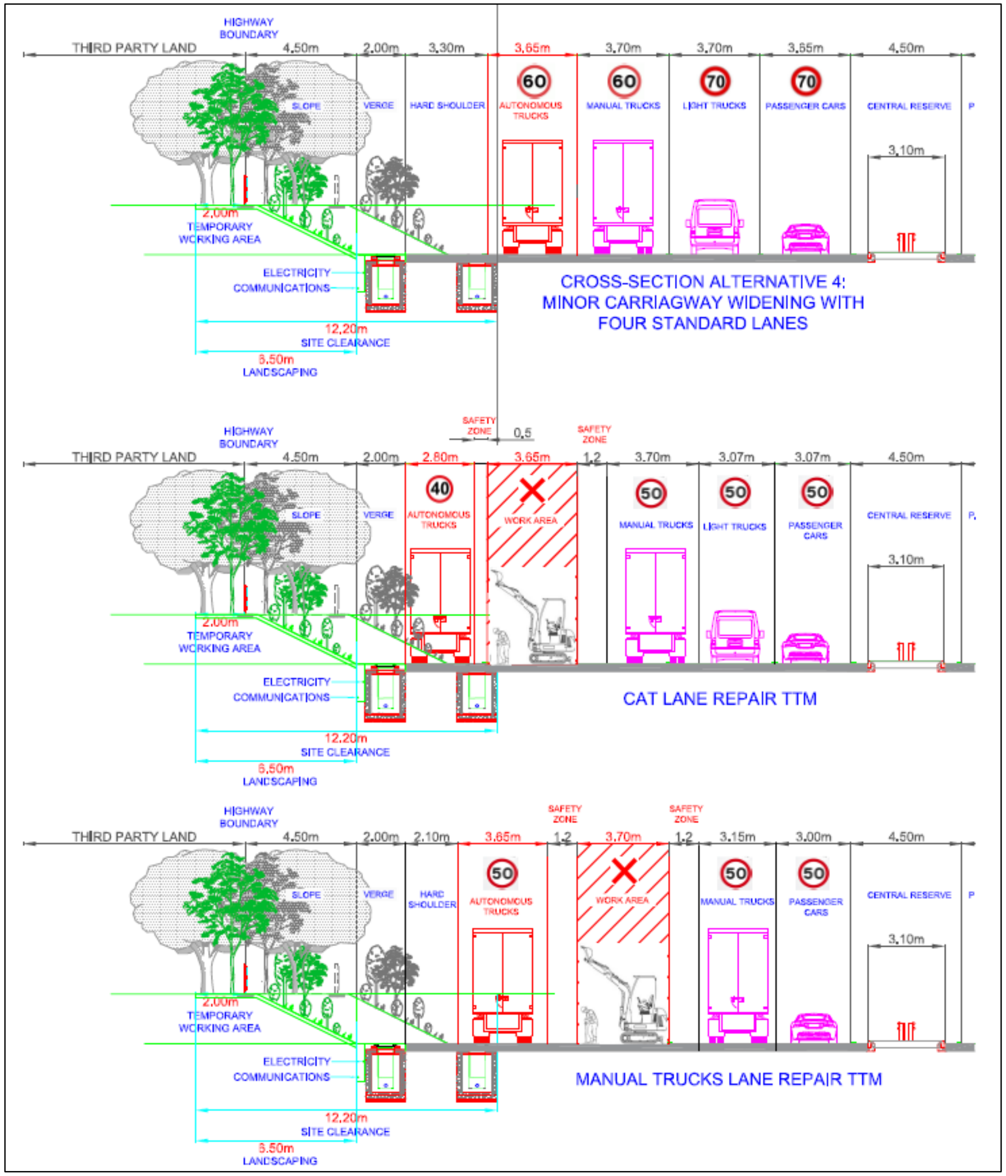


Fig. 14. Standard D4M – permanent and TTM condition

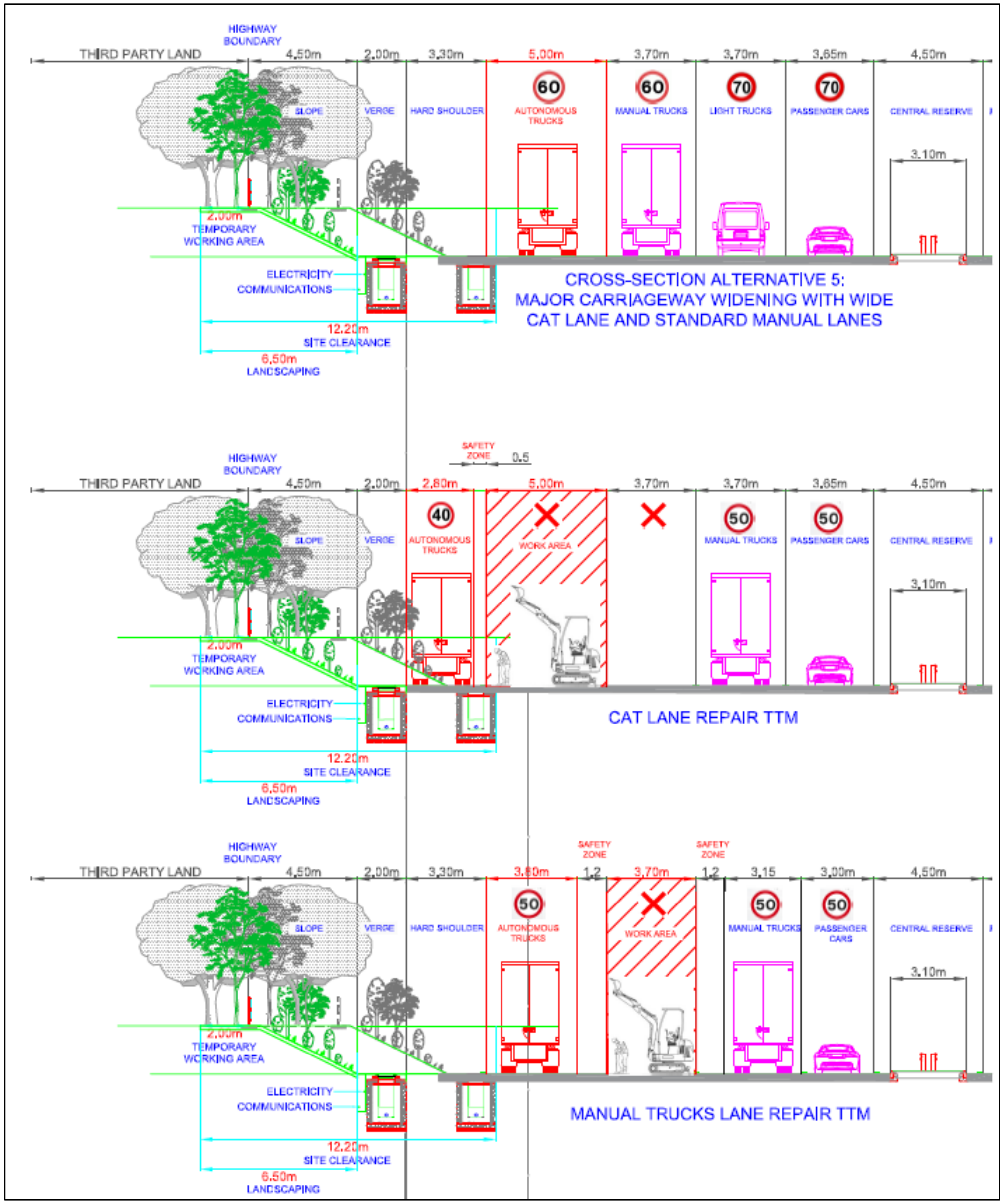


Fig. 15. Above-standard D4M – permanent and TTM conditions

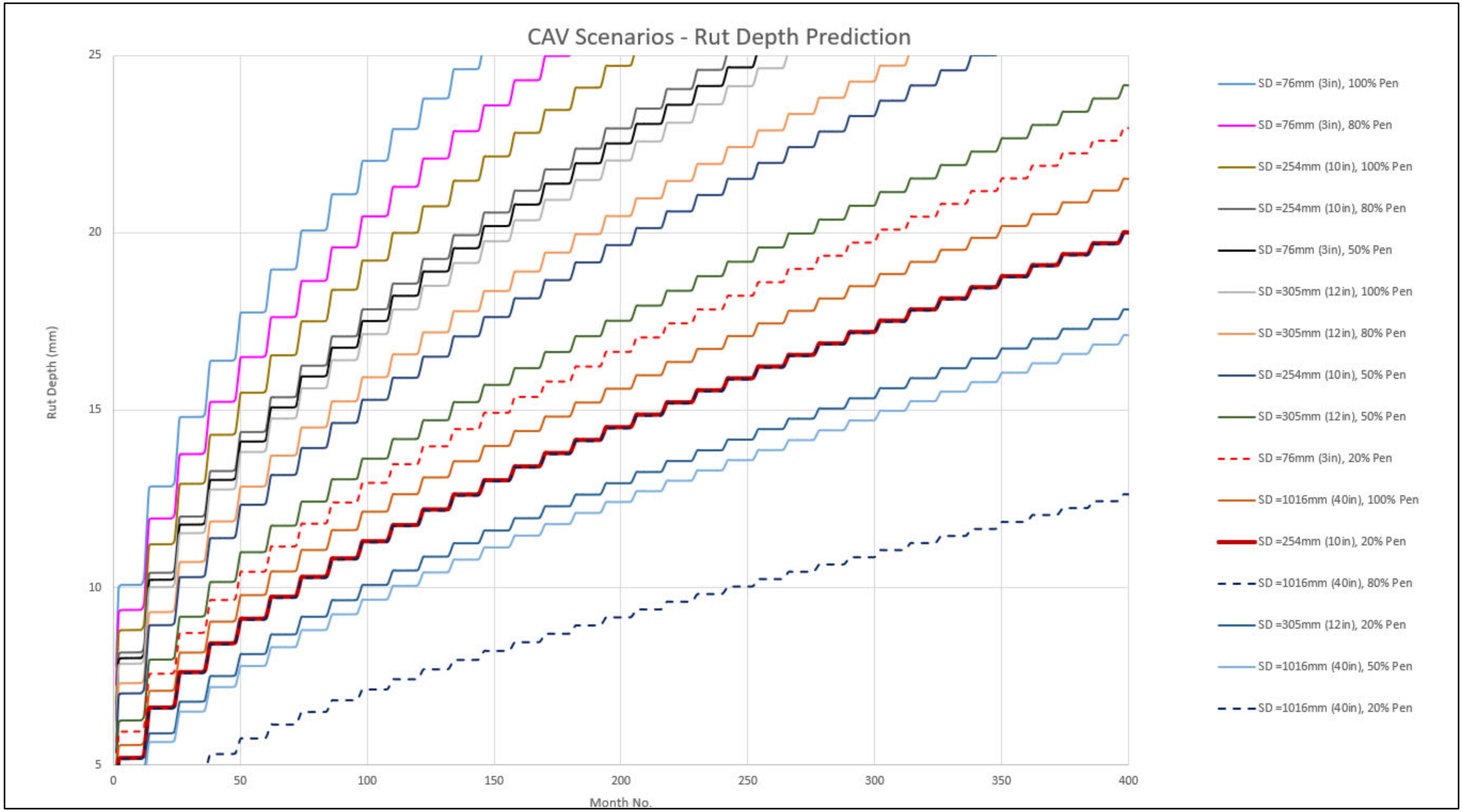


Fig. 16. Rut depth propagation curves

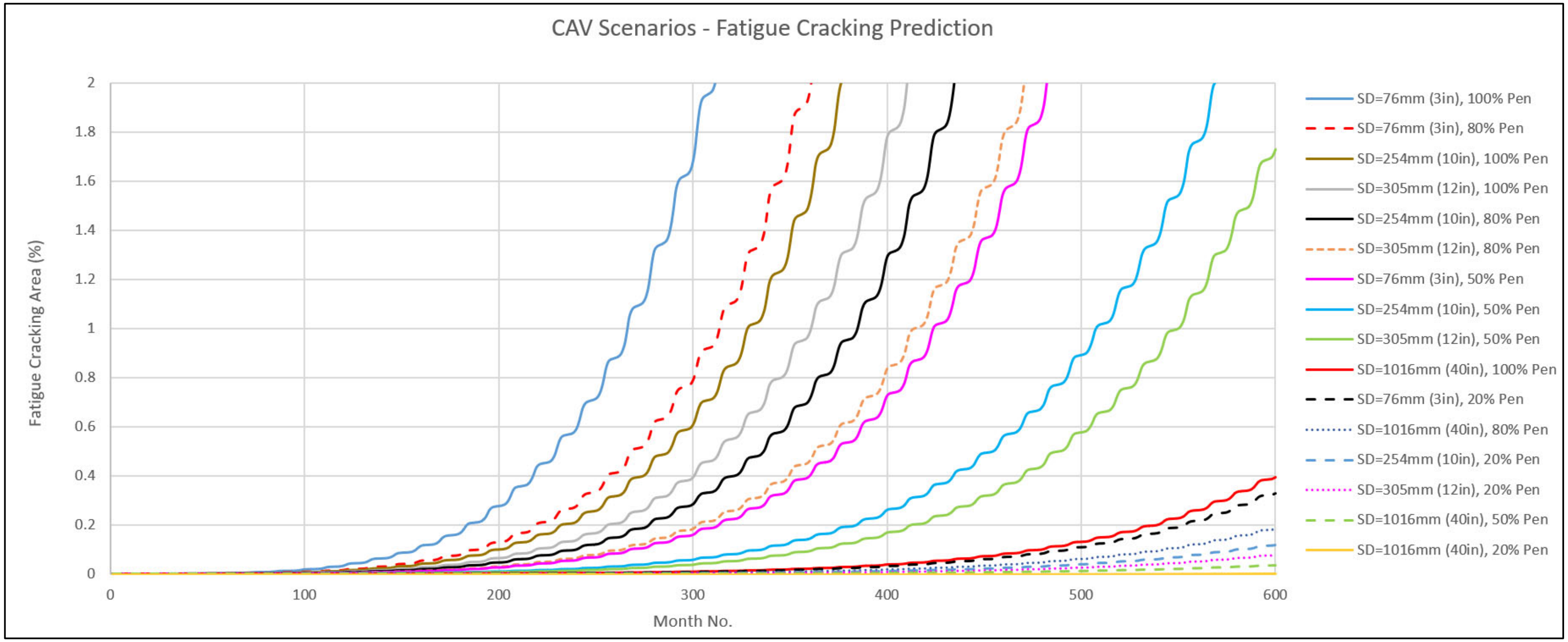


Fig. 17. Fatigue cracking failure curves

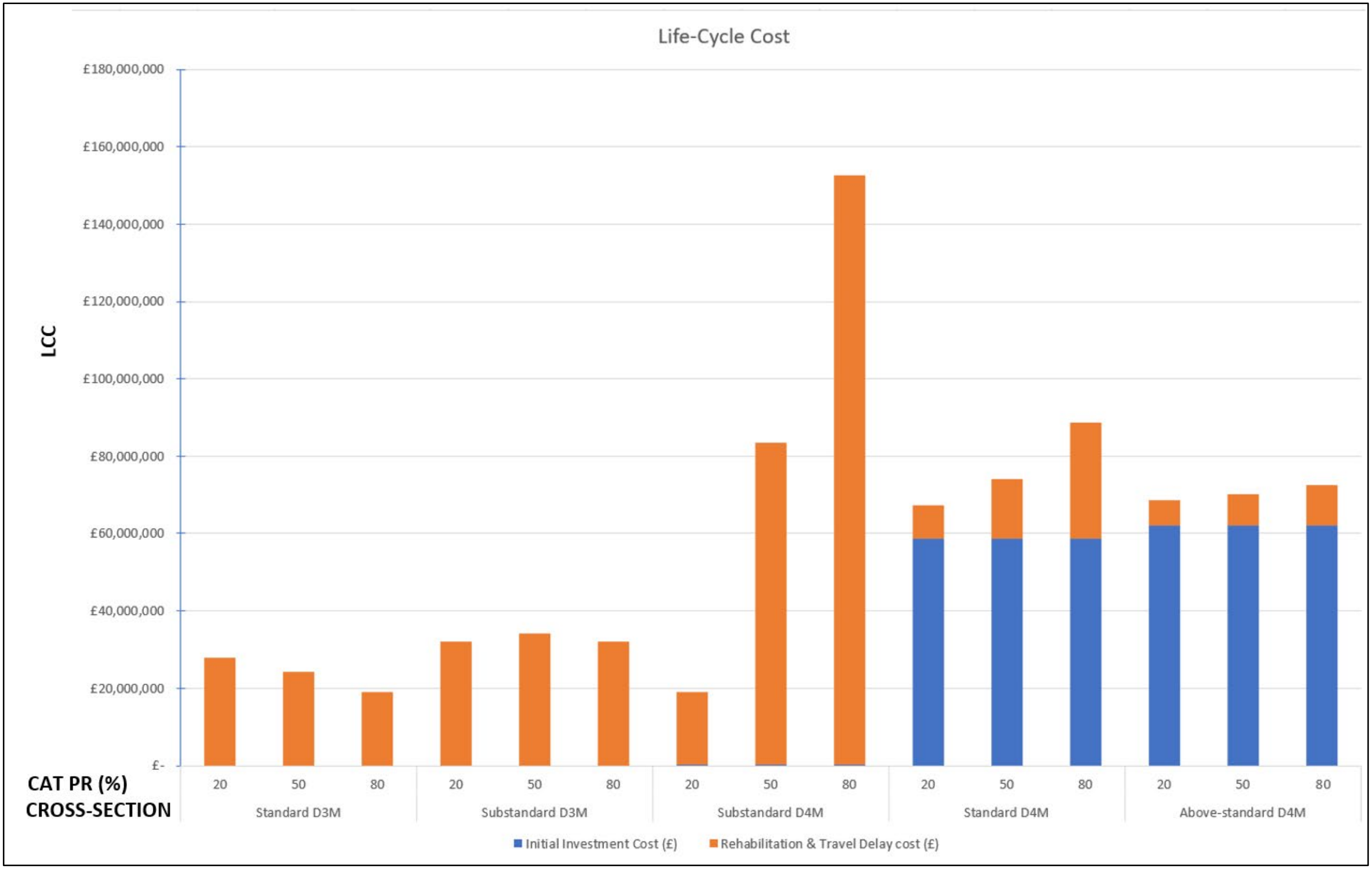


Fig. 18. Life cycle cost