

UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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Monitoring and Evaluation of Smart Motorway Schemes

by

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ABSTRACT

CIVIL, MARITIME AND ENVIRONMENTAL ENGINEERING AND SCIENCE

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Smart motorway schemes aim to address congestion issues and improve journey time reliability by utilising a set of advanced Intelligent Transport Systems applications and making use of the existing road space as much as possible. The M42 Smart Motorway Pilot, introduced in September 2006 by the Highways Agency (known as Highways England since April 2015), established the concept of Hard Shoulder Running (HSR) for the first time in the UK, together with variable mandatory speed limits during periods of congestion. Following the success of the Pilot, smart motorways are being rolled-out to other sections of Highways England's strategic road network. This research has been carried out to understand the performance of smart motorways and its limiting factors.

A review of the concept of highways capacity was carried out to understand the parameters that influence traffic conditions during smart motorway operations. This was followed by a series of analysis using empirical data which examined the performance of existing smart motorways schemes on the M42 and M6 motorways near Birmingham, UK. Overall, smart motorway schemes have significantly reduced average journey times and journey time variability, improved motorway capacity and smoothed traffic flow. The level of benefits observed varied from one scheme to another mainly due to the different site conditions (road geometry, traffic demand and patterns). However, each scheme consistently demonstrated considerable improvements when compared to non-smart motorway conditions.

One of the aims of smart motorways is to improve the distribution of traffic between lanes. Examination of the data showed that hard shoulder utilisation increased with traffic demand, however, it was potentially underutilised and influenced by the proportion of traffic leaving at the next junction. A multivariate analysis was carried out to establish a model which described motorway capacity during smart motorway operations using various traffic parameters. The findings from this research can be applied to assist in the application of smart motorways both in and outside of the UK, to reduce wasted time for commuters, business trips and freight movement.

It is recommended that the study is taken further with the newly introduced smart motorway schemes, which will include additional parameters such as local physical characteristics of the road (e.g. width, gradient, curvature) and the operation of All Lane Running.

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Academic Thesis: Declaration Of Authorship

I, Mami Jennifer Ogawa declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

[title of thesis] Monitoring and Evaluation of Smart Motorway Schemes

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. Either none of this work has been published before submission, or parts of this work have been published as:
 - *Ogawa, MJ., Poole, AJ., Meekums, RJ., Cooke, D., and Self, S. (2012). Managed Motorways: Keeping Business Moving. 19th ITS World Congress, Vienna. 22-26th October 2012.*

Signed:

Date:

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Abbreviations

Abbreviation	Description
AADT	Average Annual Daily Traffic
ALR	All Lane Running
AMI	Advanced Motorway Indicator
AMS	Advanced Motorway Sign
ATM	Active Traffic Management
BBMM	Birmingham Box Managed Motorways
CCTV	Closed-circuit television
CM	Controlled Motorways
DfT	Department for Transport
DMRB	Design Manual for Roads and Bridges
ERA	Emergency Refuge Area
HA	Highways Agency
Halogen	Highways Agency Logging Environment
HCM	Highways Capacity Manual
HOT	High-occupancy toll
HOV	High-occupancy vehicle
HSR	Hard Shoulder Running
HSR50	Hard Shoulder Running up to 50 mph
HSR60	Hard Shoulder Running up to 60 mph
HGV	Heavy Goods Vehicle

Abbreviation	Description
ILCS	Intelligent Lane Control Signals
ITS	Intelligent Transport Systems
IVD	Individual Vehicle Data
JTR	Journey Time Reliability
LOS	Level of Service
MIDAS	Motorway Incident Detection and Automatic Signalling
NEC	National Exhibition Centre
OR	Operational Regime
PIA	Personal Injury Accidents
TJR	Through Junction Running
TWT	Tuesdays, Wednesdays and Thursdays
VMS	Variable Message Sign
VMSL	Variable Mandatory Speed Limit

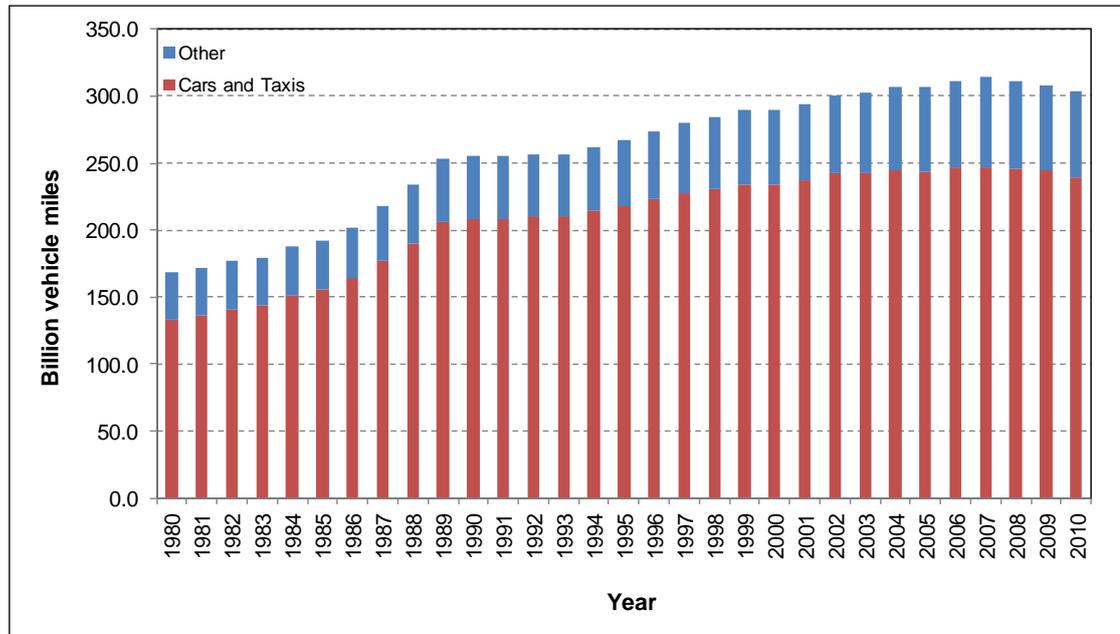
CHAPTER 1

Introduction

1.1. Background

The implementation of effective traffic management systems is essential to the nation's economic and social development (Eddington, 2006). Since the 1980s, road traffic in Great Britain has grown by 85% (Figure 1) and although a reduction in motorway traffic demand was observed since the last quarter of 2008, future traffic growth is anticipated with increasing car ownership and use (DfT, 2010).

Figure 1: Road Traffic Trends in Great Britain 1980-2010



Source: Department for Transport, 2012

The increase in traffic volume is one of the main causes of congestion, increase in fuel consumption, and its associated environmental and social problems. In 2000, The UK Government introduced the “Ten Year Plan” to address issues within transport, which included how the growing levels of congestion should be addressed (DfT, 2000).

The UK Highways Agency (HA), now known as Highways England, had a key role in the delivery of the Ten Year Plan, being tasked to develop and implement effective traffic management schemes within its strategic road network (HA, 2009c; HA 2009d). This was to be achieved through the delivery of the following key objectives:

- Making best use of the existing road infrastructure
- Responding faster to incident and reducing clear-up times
- Reducing congestion and improving journey time reliability

In Great Britain, motorways only account for 0.9% of the total road length; however, in 2010, motorways carried 19.8% of all traffic in Great Britain (DfT, 2012). When considering HGVs, approximately 80% of traffic travel on major roads (i.e. motorways and all-purpose trunk roads) and of this traffic, over 50% travel on motorways (DfT, 2012).

Figure 2: HA strategic road network



Source: <http://www.highways.gov.uk/our-road-network/our-network/>

Although some sections within the motorway network in England would require some form of widening and/or junction improvements, it was identified that alternative road traffic management measures such as Intelligent Transport Systems (ITS) could be implemented to manage congestion and make the best use of the existing road infrastructure. ITS are an innovative approach which integrates and applies the advancements in information and communication technologies to the transport sector (European Commission, 2010), enabling the various stakeholders to be better informed of real-time traffic conditions and improve journey time reliability. It has been reported that there is an average benefit of £7 for every pound invested in ITS schemes (ITS UK, 2011).

1.2. What is a smart (managed) motorway

The concept of smart motorways in the UK has evolved over the years to address growing congestion issues and concerns as to how the existing road infrastructure could be utilised in an efficient and effective manner. Smart motorways, formerly known as ‘managed motorways’, were defined within Interim Advice Note (IAN) 111/09 as a tool-box which facilitates the dynamic control of traffic for congestion and incident management (HA, 2009b). This tool-box includes various operational regimes (OR) which were been introduced on various parts of Highways England’s strategic road network, namely as follows:

- Hard Shoulder Running (HSR)
- Controlled Motorways (CM)
- Through Junction Running (TJR)
- Managed Motorways All Lane Running (MM-ALR)
- Incident management
- Ramp metering
- Dedicated lanes

The details of each OR listed above are found in Section 2.2.3.

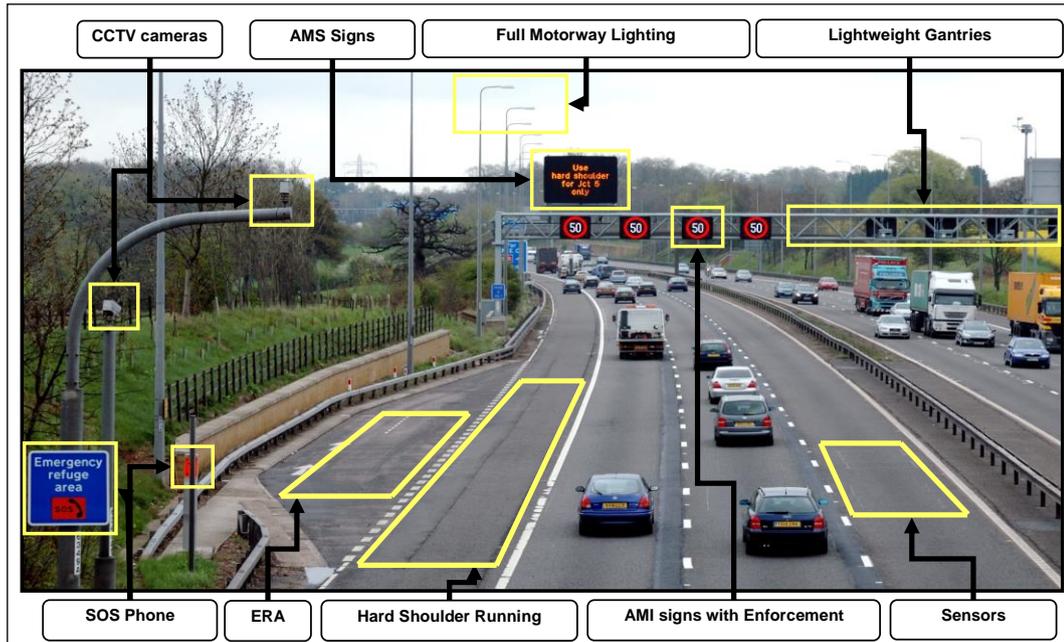
HSR is one of the key operational regimes within smart motorways and forms the main part of the research. The different ORs, where applicable, have been studied in conjunction with HSR to understand the observations made within the analysis work.

The M42 Managed Motorway (M42-MM) scheme, formerly known as Active Traffic Management (ATM), was introduced by the HA in September 2006 on the M42 between Junctions 3A and J7 (Sultan et al, 2008). The M42-MM was introduced to address congestion issues and improve journey time reliability by utilising existing road space and incorporating the following key features:

- The use of hard shoulder as a running lane (HSR) together with variable mandatory speed limits (VMSL) during periods of congestion and/or incidents
- Provision of Emergency Refuge Areas (ERAs) for broken-down vehicles
- Installation of signals and Variable Message Signs (VMS) on gantries

A schematic diagram of smart motorways and its key components are presented in **Figure 3** below. Full-motorway lighting was installed as a part of the M42-MM Pilot scheme, however, has not been required for subsequent HSR schemes.

Figure 3: Components of a typical smart (managed) motorway



Source: Sultan et al (2008)

Mott MacDonald was appointed by the Highways Agency (HA) to monitor and evaluate the performance of smart motorways, through examination of various traffic parameters and comparing the results of the 'Before' and 'After' cases. An ATM 12 month report was produced and its findings indicated that the introduction of HSR had successfully reduced congestion, improved journey time reliability and increased the observed capacity of the M42 Smart motorways section (Sultan et al, 2008). These results have added strong evidence to the benefits brought by smart motorways and led to the announcements from the DfT to roll-out this application on an additional 340 miles across England's motorway network (Unwin et al, 2009).

1.3. Objectives

With smart motorways being introduced to wider areas of Highways England's road network, it has become more important to understand the impact (both benefits and dis-benefits) and limitations of this application to inform decisions on future site selection and its life-span. Although publications such as the Highways Capacity Manual (HCM) and Design Manual for Roads and Bridges (DMRB) provide capacity estimates and descriptions of Levels of Service (in terms of traffic), to date there is no specific design guidance for smart motorway operations based on empirical analysis and research reflecting English road conditions. Therefore there is a need to gain an understanding of the limitations within smart motorways operations to support Highways England, highways designers and other key stakeholders to when making decisions on traffic management strategies to be implemented.

The objectives of this thesis are to:

- To understand how smart motorways have developed and have been applied to various schemes and establish the definition of 'capacity' within this context;
- Analyse field data from existing smart motorway sites to evaluate the probability of flow-breakdown; and
- Identifying the traffic parameters which have a statistically significant effect on motorway capacity under smart motorways operation and understand its limitations.

The research builds-up on the findings from the ATM 12 month report (Sultan et al, 2008) and explores the various Operational Regimes being introduced on smart motorway schemes following the M42 Pilot. The roll-out of smart motorways on additional motorway sections has led to the need for this thesis to research the points described above, as the ATM 12 month report was limited to:

- One smart motorway site (M42 junctions 3A to 7)
- Hard Shoulder Running up to 50 mph, and not 60mph which is currently being implemented on the Highways England network (see Section 2.3).

- Through Junction Running (see CHAPTER 6) was not implemented at the time of when the ATM 12 month report was completed.

The findings from this research have supported Highways England with the development of Interim Advice Notes and Best Practice notes relating to smart motorway operations, and selection of smart motorway sites and operational regime(s) to be implemented.

1.4. Thesis structure

The remainder of this thesis has been structured as follows:

- CHAPTER 2 This chapter provides an introduction to how smart motorway schemes have developed, how they currently operate and their future challenges. This includes an overview of smart motorway schemes within and outside of the UK to obtain an understanding of existing research within the field and the key factors which affect the performance of this type of application.
- CHAPTER 3 This chapter provides an overview of what ‘highway capacity’ is and defines the term in relation to the research objectives. It includes a review of the fundamental traffic flow diagram, the Highways Capacity Manual and other research work carried out in the field to identify key parameters which affect motorway capacity under smart motorway conditions.
- CHAPTER 4 This chapter summarises the study area, data collection and filtration requirements, and methodology adopted within the traffic data analysis. This thesis has adopted a macroscopic approach to understand the changes in traffic conditions, therefore specific analysis was required to establish the level of time aggregation.

- CHAPTER 5 This chapter summarises the key results from the HSR assessment carried out in existing smart motorway schemes in Birmingham, UK. The chapter is concluded with a table comparing the performance of smart motorway schemes in the UK to schemes in other countries.
- CHAPTER 6 This chapter summarises the key results from the Through Junction Running (TJR) assessment. The analysis includes a high-level traffic data analysis and findings from the user consultation study to evaluate the operational impact of TJR, with the overarching aim to identify factors which are potentially limiting the performance of smart motorway operations.
- CHAPTER 7 This chapter summarises the key results from the traffic demand study for the ‘Birmingham Box’, which was carried out as a result of the findings within Chapters 5 and 6. The objective of this Chapter was to understand whether the observed changes in traffic demand was a result of traffic being attracted to the smart motorway roads or general traffic growth in the area.
- CHAPTER 8 This chapter summarises the results of the smart motorways capacity study.
- CHAPTER 9 This chapter provides a study of hard shoulder utilisation, incorporating multiple linear regression analysis to model factors affecting hard shoulder utilisation and performance of smart motorway schemes.
- CHAPTER 10 This chapter summarises and discusses the key findings from this study and recommendations for future research.

1.5. Limitation of this study

The analysis has been limited to smart motorways operations on the M42 and M6 motorways in Birmingham, UK, where a lane-gain/drop arrangements and/or Through Junction Running (TJR) are in operation. The impact of All Lane Running (ALR), which is being introduced on a number of proposed smart motorway sites and later discussed in CHAPTER 5, has not been considered as a part of this research.

Smart motorways are a congestion management scheme, and not delivered as a safety or environmental scheme. The improved traffic conditions following the introduction of smart motorways have led to improved safety figures (Blaney et al, 2011) and environmental benefits (Monk-Steel et al, 2012; Hampton et al, 2012). Therefore safety and environmental aspects, although mentioned in various sections of this thesis, have not been considered within the analysis as it is beyond the scope of this thesis.

CHAPTER 2

Review of smart motorway schemes

2.1. Introduction

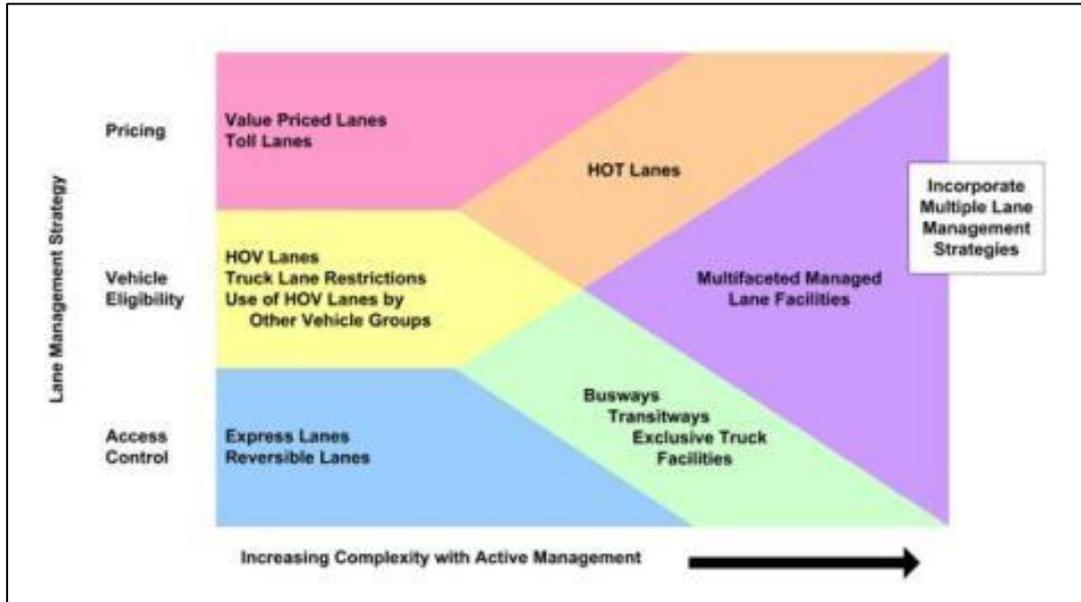
Since the opening of the Preston Bypass, the first motorway to be built in the UK in 1959, the field of highway engineering and design has been studied by many researchers and stakeholders. This chapter provides a review of current best practices, infrastructure and technologies adopted within smart motorways today through examination of:

- how smart motorway schemes have developed over the years;
- how this operational regime has been implemented and currently operates in the UK and around the world; and
- factors to be considered and challenges in relation to its operational performance.

2.2. The development of managed lane operations

As discussed earlier in Section 1.2, smart motorway scheme encompass various ORs for traffic to manage congestion. Managed lane operations have been deployed as an effective strategy to control traffic demand and capacity to improve traffic flow on motorways and aim to maintain a balance between traffic demand with road capacity, working with both dimensions of time and space. Figure 4 illustrates the various lane management operations, which have been categorised in terms of their lane management strategy (pricing, vehicle eligibility, access control) and complexity.

Figure 4: Managed Lane Applications



Source: Mirhashi et al (2007)

The following sub-sections provide an overview of the various managed lanes applications.

2.2.1. *Dedicated lanes*

Dedicated lanes include applications such as High-Occupancy Vehicle (HOV) lanes, bus lanes, and price charging. Some key examples are given below:

Pricing (tolls, congestion charging)

Pricing strategies include applications such as high occupancy toll (HOT) lanes, or congestion charging. Prices may be fixed or varied to account for periods of high traffic demand, with the aim to minimise congestion.

- Congestion charging has been implemented more widely in an urban context in cities such as London and Stockholm and effective in reducing the number of vehicles entering a section of road and/or designated area.
- The M6toll was opened in 2003, on a route between the M6 J3A and J11 as a measure to manage the high volume of traffic in the West Midlands (M6toll, 2013).

Bus Lanes

Bus lanes were introduced on the M4 between Junctions 2 and 3, where lane 3 was dedicated for use by buses, taxis and motorcycles only. However, concerns of this bus lane being underutilised were raised, resulting in traffic throughput being restricted on this section (Awani et al, 2006).

High-occupancy vehicle (HOV) lanes

High-occupancy vehicle (HOV) lanes have been one of the effective and more widely adopted managed lane strategy, particularly in North America between the 1960s and 90s (Berman et al, 2006; Mirhashi et al, 2007). HOV lane schemes were similarly adopted in the UK in 1998 on the A467 in Leeds, to manage the number of vehicles on the road whilst maximising the number of 'passenger' throughput using this section of road.

In 2008, a HOV scheme was introduced on the M62/M606 motorway near Bradford. However, it was identified by a study carried out for this scheme that over 80% of the vehicles using the HOV lanes were single occupant vehicles, highlighting that user compliance and enforcement of this type of application was difficult and an ongoing issue. The HA has considered a trial of occupancy cameras to support police enforcement, however, the effectiveness of this technology is yet to be proven in practice (HGC, 2010).

In addition to the above, safety concerns were raised in relation to driver behaviour and distribution of traffic across lanes. There is a concern that HOV lanes may result in:

- increased weaving movement of HOV and non-HOV traffic particularly at the merge and diverge areas of a junction;
- 'Undertaking' of traffic (if HOV lane utilisation is low); and
- General traffic needing to cross the HOV lane to reach the ERAs in the case of an emergency and/or breakdown.

This is due to the benefits of HOV lanes being limited to the proportion of multiple occupancy vehicles, as this would affect the distribution of traffic and speed differential across the running lanes. As a result the remaining road users on other running lanes (i.e. single occupancy vehicles) may potentially experience congestion as the existing road space would not be used effectively under such circumstances.

Although the safety analysis conducted for HOV lanes in the US demonstrated that the Annual Average Daily Traffic (AADT), areas of merge and diverge, environment (climate, light) were the key factors affecting the crash frequency and not the lane management strategy itself (Lee et al, 2007), subsequent HOV lanes on UK motorways were cancelled with the concerns associated with driver behaviour and findings from the M62/M606 motorway (HCG, 2010).

2.2.2. Ramp metering

Ramp metering systems address congestion issues and aim to improve journey time reliability by introducing a dedicated traffic signal on the ramp (on-slip) which is controlled by an algorithm that monitors traffic on both the main carriageway and the ramp. The signals work on a part-time basis, coming into operation as traffic levels increase on the main carriageway, in particular, during the peak-periods, preventing the occurrence of flow-breakdown by:

- Regulating the amount of traffic joining the main carriageway; and
- Managing the flow on the on-slip to avoid large platoons of vehicles joining the main carriageway, thus enabling traffic to join the motorway more smoothly and safely.

Ramp metering is not a new or uncommon lane management application and has been introduced on many motorways worldwide in countries such as Germany, Holland, France, and Japan. It is commonly found within the United States with more than 2200 sites implemented since the early 1960s.

Ramp metering was introduced in the UK in 1986 at M6 Junction 10, and subsequently developed and trialled at the M3/M27 in 1998. Following the completion and evaluation of the M3/M27 project in 2005, ramp metering has since been rolled-out to an additional 30 ramp metering sites during 2006/2007 and 85 sites were in operations by the end of 2009. The advantages and disadvantages of ramp metering systems are summarised in Table 1 below.

Table 1: Advantages and disadvantages of ramp metering operations

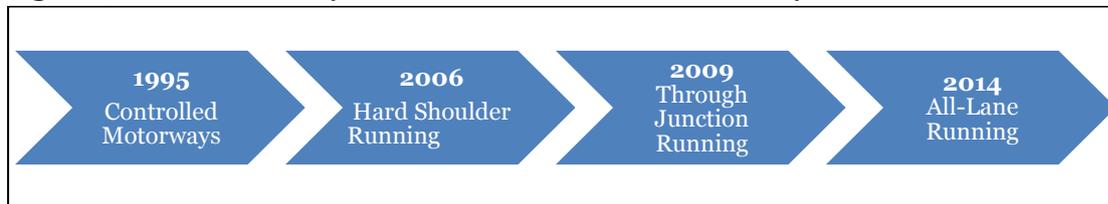
Advantages	Disadvantages
Improvement in journey time reliability	Waiting on the on-slips may be frustrating to road user accelerating to join the main carriageway
Prevents/reduces the occurrence of flow-breakdown on the main carriageway	It may result in some road users ‘rushing’ through the green light
Smooth and safer merge from the on-slip to main carriageway	Operation may not be efficient depending on equipment settings (e.g. fixed time vs dynamic)
Reduced environmental impact (noise and air pollution)	Queues may spill back to the upstream junction (e.g. roundabout)
Reduced congestion	HGVs may struggle to gain speed to join the main carriageway as the length of acceleration reduces if stopped by the traffic lights

Ramp metering has been operational on six sites of the M42-MM section, at Junctions 4, 5 and 6 in both northbound and southbound directions. However, the number of days during which ramp metering was activated during smart motorways was very small, due to the improvement in traffic conditions as a result of HSR operations. This calls into question the current effectiveness of ramp metering at these sites (Sultan et al, 2009).

2.2.3. *Multifaceted managed lane management strategies*

The multifaceted managed lanes, depicted in Figure 4, integrate a number of lane management strategies which offer flexibility in their operation and benefits to a larger number of road users. This type of application offers a more cost-effective solution compared to a conventional road widening scheme through implementation of dynamic road control measures (e.g. variable speed limits, message signs, opening of the hard shoulder), adapting to road conditions specific to that moment in time. Figure 5 illustrates the timeline of ORs introduced on UK motorways.

Figure 5: Timeline of key ORs introduced on UK motorways



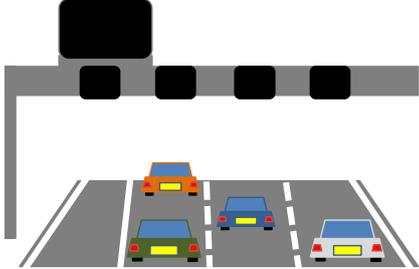
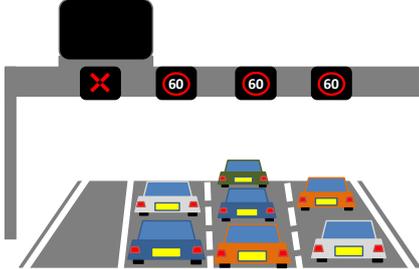
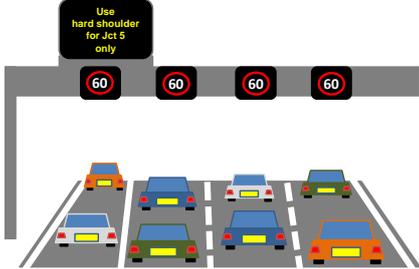
Controlled Motorways (CM)

CM utilise Variable Mandatory Speed Limits (VMSL) across the main carriageway during periods of congestion but does not utilise the hard shoulder as an additional running lane. CM was first introduced in the Netherlands in the 1980s and is also known as ‘speed harmonisation’ in countries outside of the UK. CM was first introduced in the UK in 1995 on the M25, and is currently operational on sections of the M25, M42 and M40.

Hard Shoulder Running (HSR):

As described in Section 1.2, the hard shoulder is temporarily opened as an additional running lane alongside with VMSL during periods of heavy congestion or incident. This OR was first introduced on the M42 motorway between Junctions 3A and 7, and has since been rolled out to other links on the M6. The overarching aim of VMSL is to smooth traffic flow by reducing the differential speed between lanes (i.e. more uniform flow). The signal settings and their timings are set in accordance with pre-determined thresholds, calibrated on a link-by-link basis, based on real-time traffic data. Figure 6 illustrates the opening sequence of a smart motorway HSR scheme.

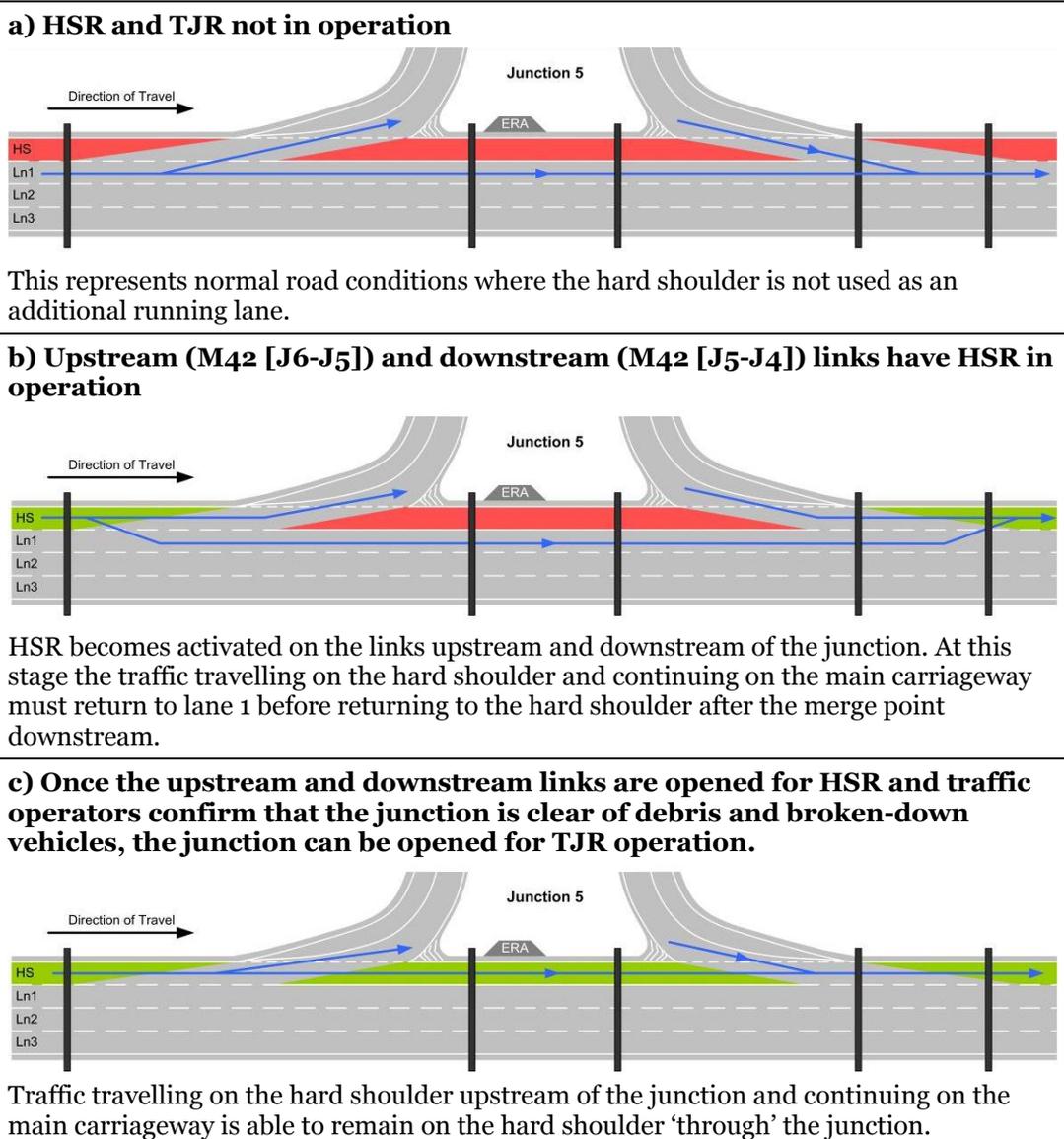
Figure 6: Opening sequence of HSR schemes

	<p>HSR not in operation (normal road conditions)</p> <p>This is essentially normal road conditions where the national speed limit is in place and hard shoulder is not used as an additional running lane.</p>
	<p>CM becomes operational</p> <p>When traffic levels increase, the red-x (lane control) is displayed on the hard shoulder and VMSL are displayed (i.e. CM becomes operational).</p> <p>During this phase, a 'sweep-through' exercise is carried out by traffic officers and CCTV to check the hard shoulder is clear of obstructions.</p>
	<p>HSR becomes operational</p> <p>The hard shoulder is opened to traffic once the hard shoulder is checked that it is clear of obstructions/debris (i.e. safe to open the hard shoulder).</p>

Through Junction Running:

TJR was introduced at Junction 5 on the M42 in the southbound direction on the 9th December, 2009. This OR enables road users to use the hard shoulder 'through' the junction, instead of the lane drop/gain arrangement introduced within the Pilot scheme. TJR operates on a part-time basis (during periods of congestion) at the M42 J5 southbound site, where the hard shoulder is opened when HSR becomes operational on its upstream and downstream links, and on a full-time basis at M6 Junction 10. The operation of part-time TJR is described in Figure 7.

Figure 7: Opening sequence of TJR

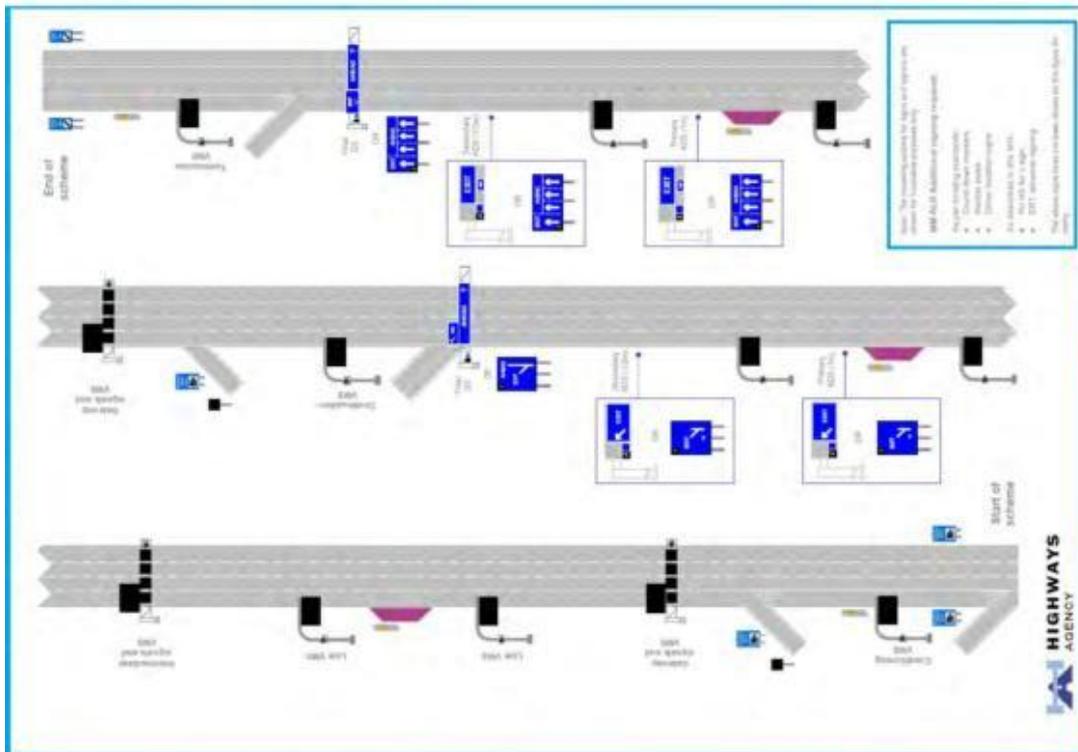


The existing sites were deemed suitable for TJR as the majority of traffic at these junctions (approximately 88%) continues on the main carriageway. This is discussed further in CHAPTER 6.

Smart Motorways All Lane Running (SM-ALR)

At the time of writing, Highways England are in the process of introducing Smart Motorways All Lane Running (SM-ALR) as a new OR. SM-ALR adopts the principles of HSR, and involves the conversion of existing hard shoulders to be a permanent running lane. Figure 8 shows an illustrative drawing of SM-ALR depicted within IAN 161/12.

Figure 8: Illustrative drawing of MM-ALR



Source: Highways Agency (2012),

The key differences between existing HSR and SM-ALR projects are as follows:

- SM-ALR is less visually intrusive with increased spacing and reduced number of portal gantries (i.e. gantries spanning across the main carriageway with AMI mounted above each lane)
- Use of verge signs and cantilever gantries to supplement the reduction in portal gantries.
- The permanent conversion of the hard shoulder removes the need for the complex procedures associated with the opening/closing of the hard shoulder.
- ERA spacings are increased up to 2.5km.

SM-ALR schemes have not been considered as sufficient traffic data was not available to carry out a robust analysis at the time of writing.

Focus of this research

As discussed in Sections 1.3 and 1.5, this thesis has focused on HSR operations. Although SM-ALR schemes are currently under construction, HSR operations still continues to be rolled-out on Highways England's roads where SM-ALR is considered to not be a feasible solution (e.g. limited road space, required land space, availability of hard shoulder, etc.) therefore are still applicable to future schemes.

2.3. Smart motorway sites in Birmingham, UK

The M42 smart motorway (formerly known as Active Traffic Management or Managed Motorway), between Junctions 3A and J7, covers a distance of approximately 17 km. This route is a dual 3-lane motorway, comprised of four links which are fairly equal in length (with the exception of the [J5-J6] link which is 5.2 km long and slightly longer than the others). The topography is reasonably flat with lane widths including the hard shoulder varying in width from 3.3 m to 3.7 m¹. The M42 is also one of the busiest motorways in the UK with the average daily traffic ranging from 50,000 to 75,000 vehicles per direction (Sultan et al, 2008). Junction 6 provides the main access to Birmingham International Airport and the National Exhibition Centre (NEC).

Since 30th November 2009, the Birmingham Box Managed Motorway Phase 1 (BBMM1) scheme has also become operational on the M6 between J4 and J5, M42 between J7 and J9 and M40 J16 to M42 J3A. The approximate link length between J4 and J4A is 4.7 km and the link between J4A and J5 is 3.2 km long. J4A is a movement-restricted junction with a single lane merge/diverge. In the northbound direction, J4A acts as a merge between the slip road of the M42 and the M6, whilst in the southbound direction it acts as a diverge from the M6 towards the M42.

¹ Lane widths were modified with the introduction of the M42-ATM pilot scheme to ensure that the hard shoulder was wide enough to be used as a running lane.

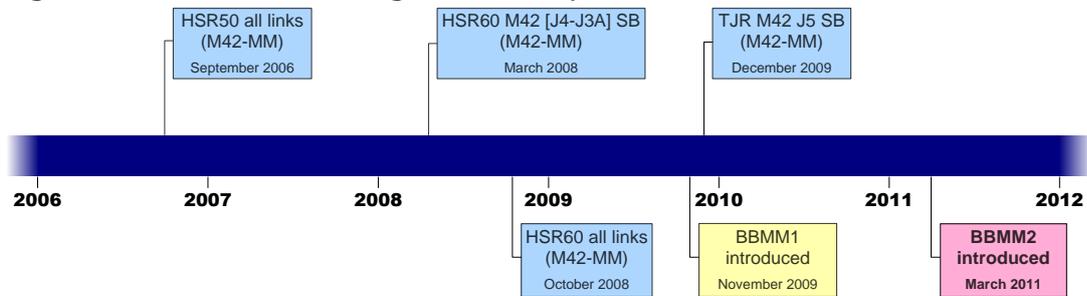
In addition to HSR, Through Junction Running (TJR) was introduced at J10 on the M6 in both the northbound and southbound directions. M6 J10 is the first site in the UK to introduce full-time TJR, enabling motorists to utilise the hard shoulder at any time day or night.

Figure 9: Location plan of existing managed motorway schemes in Birmingham, UK



Figure 10 summarises the timeline of events leading to the introduction and operation of BBMM Phase 2.

Figure 10: Timeline of managed motorway schemes



The M42-SM initially operated HSR up to 50 mph (HSR50) until October 2008, when HSR up to 60 mph (HSR60) was introduced. Based on the benefits observed following this increase in speed limit, 60 mph has been the maximum operating speed during HSR for BBMM1&2 since they opened (Ogawa et al, 2009b, 2011a, 2012a).

A high-level study was carried out by the researcher to evaluate the impact of HSR on traffic conditions at the existing smart motorway schemes in Birmingham, UK. The results are discussed later in CHAPTER 5.

2.4. HSR schemes in other countries

This section provides an overview of HSR schemes introduced outside of the UK, including a summary of their operational aspects and operational impact.

2.4.1. Netherlands

As mentioned in Section 2.2.3, the concept of ‘speed harmonisation’ was first introduced in the Netherlands during the 1980s and has since been implemented on approximately 1000 km (620 miles) of the Dutch road network (Helleman, 2005). During the last decade, Rijkswaterstaat (part of the Dutch Ministry of Transport) was unable to procure road widening schemes due the development of the European legislation relating to emission levels. Following the success of the speed harmonisation schemes, temporary right shoulder use (i.e. HSR) was developed in 1996 to provide additional capacity to existing road network without constructing a new motorway or motorway widening (OECD, 2010).

In 2003, the Emergency Road Widening Act was passed by the Dutch Parliament which enabled HSR schemes to be introduced within a shorter time-scale to address the immediate issues associated with the nation’s existing congestion issues (UNECE, 2003). As of 2010, there were 300 km of HSR schemes operational in the Netherlands, as presented in Figure 11 (Grontmij, 2010).

Figure 11: Existing and proposed HSR schemes in the Netherlands



Source: Adam, 2007

Operational Aspects

The Dutch managed motorway schemes are delivered through the Motor Control and Signalling System (MCSS), which are operated by its national and regional traffic control centres. The opening of the hard shoulder is notified to the road users using the signals mounted on the overhead gantries, where a green arrow and VMSL are displayed as shown in Figure 12.

Figure 12: Hard Shoulder Running in the Netherlands



Source: Helleman, 2007

As of September 2012, the national speed limit in the Netherlands is up to 130 kph (~81 mph) on motorways and 100 kph (~62 mph) on national roads (Rijksoverheid, 2012). During speed harmonisation, three speed limits are utilised similar to the UK projects: maximum speed limit of 90 kph (56 mph), and additional settings of 70 kph (44 mph) or 50 mph (31 mph) depending on traffic levels (Helleman, 2007).

To minimise the risk of road users being confused as to whether the hard shoulder is open or not, the Dutch have adopted the road signs displayed during HSR from German schemes as shown in Figure 12 above. Following some safety concerns associated with bad compliance which was raised during initial operations, a red-X signal is also displayed above the hard shoulder lane during periods where HSR is not in operation (Helleman, 2007).

Overview of the HSR infrastructure

As a part of the HSR schemes, the following infrastructures have been installed:

- Emergency Refuge Areas (ERAs) located every 1000 m.
- Traffic sensor loops installed every 500 – 600 m on the main carriageway and every 75 m on the hard shoulder.
- Gantries displaying overhead arrows and speed limits installed every 700 m

Operational Impact

The HSR schemes implemented in the Netherlands have provided various benefits to the Dutch road network, where an increase in motorway capacity between 7 and 22% and average journey time improvements of 4% (~ 3 min/km) were observed. The schemes have also reported no negative impact on road safety, and regarded to be up to 2.5 times more cost effective than a conventional road building scheme (Staufreies, 2010).

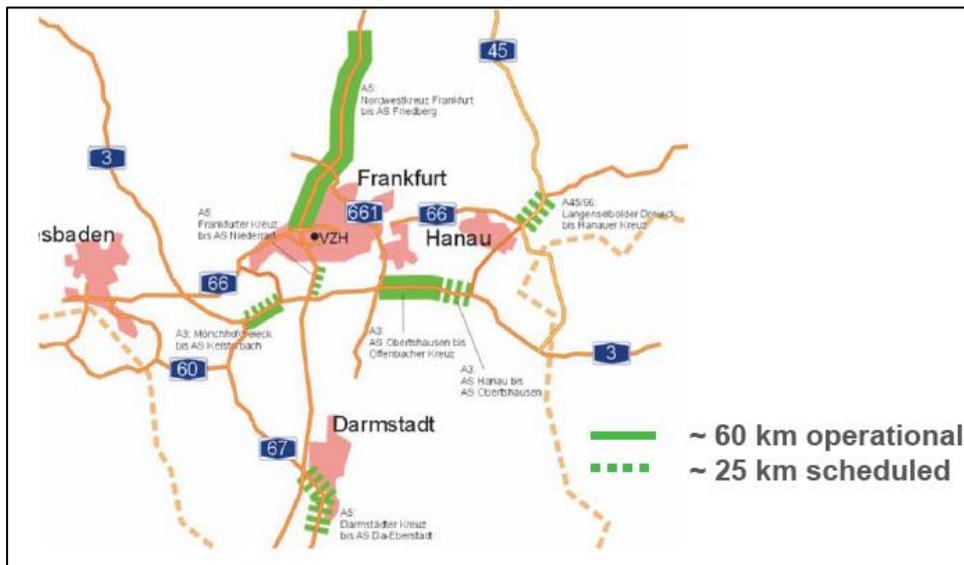
2.4.2. Germany

Since its re-unification, Germany has experienced large levels of road traffic growth and as of 2007 anticipated a 16% increase in road users by 2015 (Mirshashi et al, 2007). 57% of Germany's congestion is due to high volumes of traffic, and as a result, Germany has implemented a major road building programme to be completed by 2015, which includes the following (Sparmann, 2007):

- 1730 km of new motorway
- 2162 km of motorway widening
- 717 new bypasses

This expansion required the country to provide an additional 15 regional control centres to enhance the management of their roads and existing managed motorway schemes.

Figure 13: Existing and Proposed HSR schemes in Frankfurt as of 2008



Source: Riegelhuth, 2007

HSR was first introduced in 1996 and to date has been rolled-out to 200 km of Germany's road network (OECD, 2010). As of 2012, 85 km of HSR projects were in operation near Frankfurt (see Figure 13). 12 km of the proposed 25 km route is currently at the implementation stage on the A5 between the Darmstadt interchange and the Eberstadt junction in both directions (Staufreies, 2010).

Operational Aspects

The German HSR schemes commence operation once the traffic flows reach approximately 6000 veh/hr. One of the key differences between the German and HSR in other countries is that it requires no human intervention (although it can be controlled manually as and when required); the operation is automated based on traffic conditions within a pre-defined algorithm (Mirshashi et al, 2007). During operation of the hard shoulder, the maximum speed limit is reduced from 120 kph (75 mph) to 100 kph (62 mph), and runs between and through junctions. **Figure 14** shows the hard shoulder being utilised by vehicles on the A5 Hessen scheme. A rotating prism sign is also positioned on the motorway verge indicating that HSR is in operation.

Figure 14: Hard Shoulder Running in Germany



Source: Sparmann, 2007

Overview of the HSR infrastructure

As a part of the HSR schemes, the following infrastructures have been installed:

- The standard 3.75 m lanes were reduced to 3.50 m wide
- Narrow strips on both inside and outside lanes as there are no ERAs.

- Gantries displaying overhead arrows and VMSL installed every 800 to 1000 m. Contrary to the Dutch system, the VMS do not display a signal on the hard shoulder lane whilst HSR is not in operation.
- CCTV cameras installed every 750 m. Although these cameras have video detection capabilities to identify incidents on the hard shoulder, a fully automatic incident detection system has not yet been implemented (Sparmann, 2007).

Operational Impact

To date, the HSR schemes introduced in Hessen have demonstrated various benefits. Average journey times along the routes have reduced up to 20% and an increase in motorway capacity of 25% and overall traffic throughput was also observed. There has also been no negative impact on safety aspect, with a significant reduction in accidents on the approach to the HSR section being noted (Blaney et al, 2011).

2.4.3. France

HSR was first introduced in France on the A3-A86 trunk road where the road section suffered from saturated levels of traffic prior to the completion of the A86 motorway. Road widening was not a feasible solution to resolve this problem as the site was situated on a curved viaduct; hence HSR was considered as an alternative solution and subsequently implemented (Cohen, 2004). Following the success of the A3-A86 scheme, an additional HSR scheme was introduced on the A4-A86 corridor near Paris (OECD, 2010).

Figure 15: Temporary HSR in France



Source: Toffin, 2008

Overview of the HSR infrastructure

The French schemes have introduced an ‘intelligent shoulder’ solution which utilises dynamic lane closure barriers found at 300 m intervals along the HSR sections (Toffin, 2004; 2008). These barriers indicate whether the hard shoulder is available as a running lane in a clear manner and are controlled remotely and slow moving; hence enabling a safe and smooth opening/closure of the HSR operation.

Figure 16: Dynamic Lane Closure Barriers



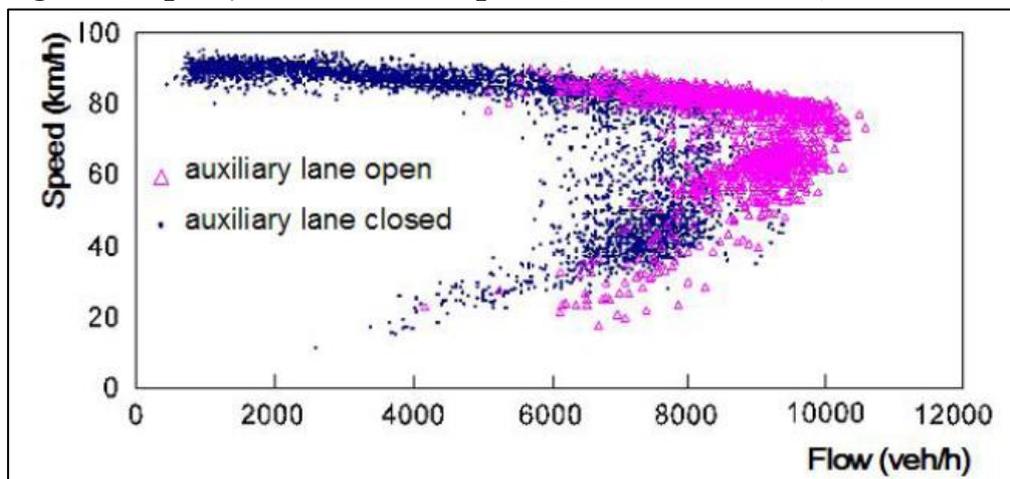
Source: Desnouailles, 2007

CCTV and video detection technology have also been introduced to detect the onset of flow-breakdown or incidents more effectively, as this would minimise the workload for traffic officers without having to constantly monitor the vast number of cameras deployed (Cohen, 2004).

Operational Impact

Both HSR schemes introduced in France have shown that HSR reduced the level of congestion and improved the overall level of service throughout the corridor. The A3-A86 and A4-A86 trials have shown an increase in observed motorway capacity of 7%-16% and 7.5%-10% respectively, with journey time improvements up to 50% also being observed (Toffin, 2008). Specifically, the A4-A86 showed an average increase in maximum throughput of 900 veh/hr, as presented in **Figure 17**. Reduction in air emissions, noise levels and accidents were also noted from both trials.

Figure 17: Speed/Flow Relationship at A4-A86 HSR scheme, France



Source: Desnouailles et al, 2007

2.4.4. *Italy*

In Italy, an HSR scheme known as the T3 project was introduced on a motorway near Mestre, and demonstrated similar benefits to those observed within other HSR projects. The evaluation of the T3 project showed an average increase in traffic throughput of 7.5%-8% and up to 12.5% and increase in average speeds of 15 km/hour (which led to an improved journey times). One of the notable benefits from this scheme was the reduction in the number of accidents, ranging between 50-70% in each direction within the scheme extents (Highways Agency, 2010).

2.4.5. USA

Over the years, the United States has introduced various Managed Motorways schemes throughout the country, including HOV lanes to dedicated bus lanes throughout the nation’s busiest highways. HSR is currently in operation on the I-66 in Fairfax, Virginia, and a unique feature to this section is the use of the lane adjacent to the central reserve as a temporary HOV lane during HSR operation. The speed limits during HSR and non-HSR operations are limited at 55 mph (88 kph), and the scheme has reported an improvement in road capacity along this route (DfT, 2008). Some of examples and their key features are summarized in Table 2 below.

Table 2: Existing managed motorway projects in the US

Project	Key features
I-66 (Fairfax, Virginia)	HSR is currently in operation at fixed times during of the day. The section also uses of the lane adjacent to the central reserve as a temporary HOV lane
New Jersey Turnpike	Toll road in New Jersey. Active signage used since the 1960s.
I-35, I94 (Minneapolis, Minnesota)	Uses Intelligent Road Information System (IRIS), which operates ramp metering, VMS and loop detectors Includes high-occupancy toll lanes
I-5, I-90, SR520 (Washington)	I-5 ATM project introduced in August 2010 ATM project in Seattle is fully enforceable

The Washington State Department of Transportation (WSDOT) has completed a number of Active Traffic Management projects on motorways in the Seattle area, Figure 19 shows a photograph of where VMSL are being implemented during the peak period; note that the speed limits are not the same across all the running lanes, which is a key difference from the smart motorway projects in the UK.

- Intelligent Lane Control Signals (ILCS) above each lane at approximately 800 m intervals
- VMS accompanying the ILCS
- 12ft (3.65m) lane widths with 3ft (0.91m) hard strips
- Speeds are determined automatically and decrease at no more than 10 mph, and intervals of 5 mph are also common.
- Red-X signals are displayed during incidents.
- Operators are able to override the HOV designations and open the HOV lanes to regular traffic when required.
- There are plans for express toll lanes to be introduced on the I-405.

Operational Impact

The various applications of smart motorway in the US have demonstrated improvements in journey time and journey time reliability. However, it was noted that there is scope for improvement with the speed limit compliance with VMSL.

2.5. Summary

This chapter provided an overview of how smart motorways has developed and examined HSR schemes outside of the UK and their current best practices, infrastructure and technologies adopted. The schemes studied have all demonstrated how this type of application has been effective in addressing congestion, providing additional road capacity and giving improvements in journey times (associated with improvements in traffic speeds) in an effective and efficient matter.

The findings from this chapter is later be compared to UK smart motorway conditions in CHAPTER 5, to help understand how they currently operate within the UK and identify the factors to be considered and challenges in relation to its operational performance.

CHAPTER 3

Review of motorway capacity

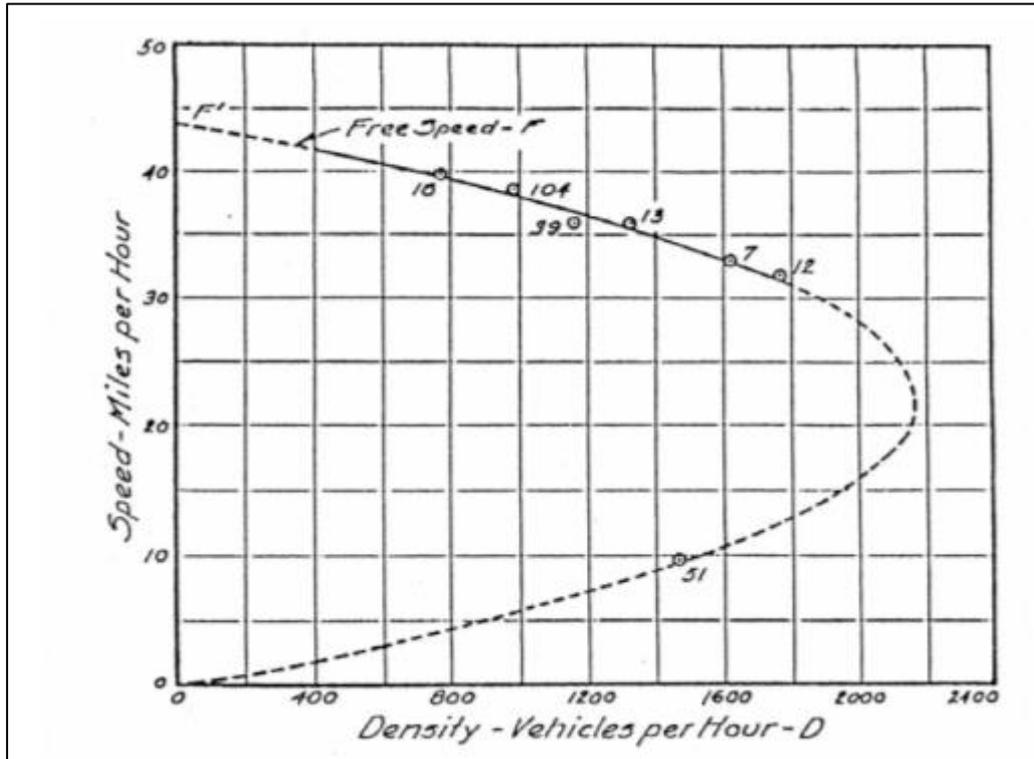
3.1. Background

Over the years, the term “capacity” has been interpreted in many different ways and various concepts have been introduced. In the literal sense, capacity can be defined as the maximum flow which can reasonably pass through a given point or section of road (OECD, 1983; TRB, 2000). However, capacity can also be represented in relation to flow thresholds which ensure good levels of service; i.e. the flow which produces a minimum acceptable speed and also as the maximum traffic volume for comfortable free-flow conditions. This section provides a literature review the various concepts of capacity, how highway capacity is measured, and to identify a definition that can be applied to this research.

3.2. The fundamental traffic flow diagram

In 1935, the fundamental traffic flow diagram, representing the relationship between traffic speed and flow in the context of highway capacity was published by Greenshields (Greenshields, 1935). Following Greenshield’s research, this discipline has been researched by a number of transport researchers and practitioners, to better understand and apply this concept to accurately estimate highways traffic flows and road capacity.

Figure 20: The first fundamental speed/density diagram



3.3. The Highway Capacity Manual

A research undertaken by Nielsen identifies the lack of European references in relation to the estimation of speed/flow and flow/density relations on the motorway network outside of the United States (Nielsen et al, 2008). The United States' Highway Capacity Manual (HCM) has been one of the most comprehensive works and a common reference source to much research undertaken in this discipline. The HCM 2000 defines capacity as follows (HCM, 2000):

The capacity of a facility is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions.

This definition expects the capacity for a given road network to be a flow rate that can be sustained over a period of sufficient demand and not the absolute maximum flow rate observed.

3.3.1. *Level of Service*

Another concept of traffic capacity introduced within the HCM is the Level of Service (LOS). The LOS classifies the varying traffic flow conditions which may range from free-flow to stop-start conditions. The classification of each level is based on the density of vehicles; i.e. the higher the density, the lower level of service. This type of approach may relate the maximum flows observed at different LOS in terms of the sustainability of the road section in consideration (i.e. environmental and cost-benefit points of view).

3.3.2. *Theoretical Capacity*

When undertaking an assessment of a new road construction or junction design, capacity may be determined from the relevant design standards which indicate a “theoretical capacity” of the road section in consideration. For example, the Cost Benefit Analysis (COBA) manual identifies the typical maximum flow of a motorway section to be 2300 veh/hr/lane² (DMRB Vol. 13.1.5) whereas the Design Manual for Roads and Bridges (DMRB) TD22/06 Clause 3.2 identifies the capacity as 1800 veh/hr/lane.

The 1800 veh/hr/lane identified in TD22 is based on the “two-second (headway) rule” advised in the Highways Code, and does not represent the maximum hourly throughput which can be achieved by a given motorway section. However, it also notes that flows greater than these values can usually be associated with decreasing levels of service. Theoretical values cannot be used as part of the capacity analysis as these values are too “ideal” and do not consider the varying factors which may affect the actual capacity of the road³.

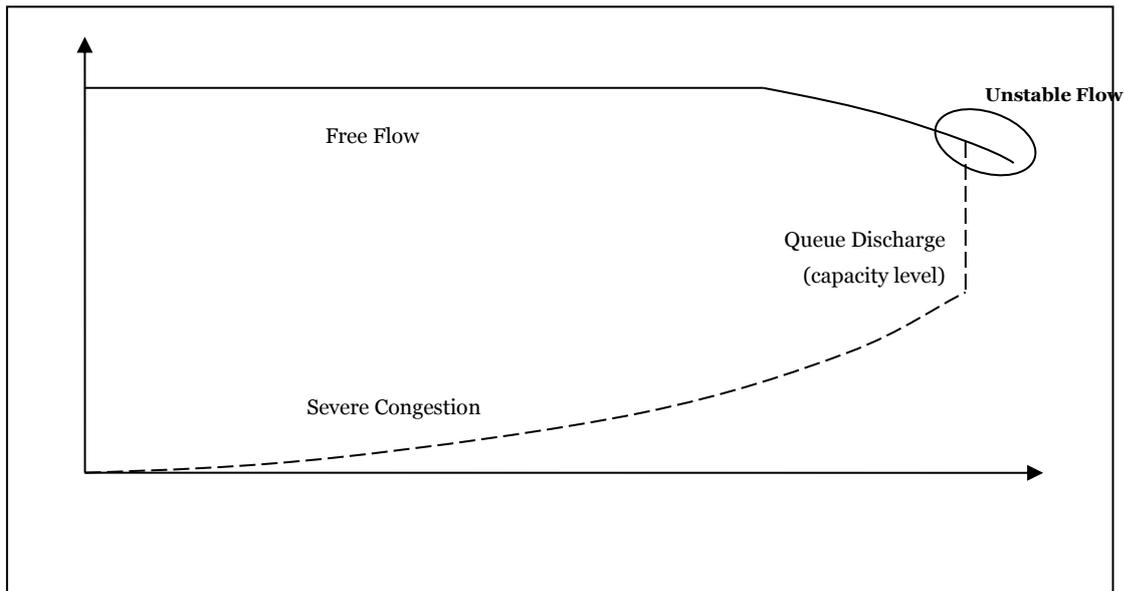
² This figure is based on the percentage of Heavy Goods Vehicles (HGV) being 2% (minimum typical value) and that vehicles are also travelling to their speed limit

³ Note however that designers are expected to have a general understanding of the effect of such variables (these factors are discussed in Section 3.4).

3.3.3. Observation of Capacity

Figure 21 is a schematic diagram of a speed/flow relationship curve. In this graph, three main segments which illustrate the varying traffic conditions found during periods of high traffic demand have been identified (Hounsell et al, 1994):

Figure 21: Schematic Diagram of Speed/Flow Relationship



Free Flow: This part of the curve corresponds to traffic in a fluid state (i.e. the system is elastic), where vehicles do not hinder each other's movements. The speed declines as the flow increases, until the latter reaches a critical value or level, which is identified as the state of unstable flow within the diagram.

Queue Discharge: Beyond this critical threshold, flow-breakdown occurs (i.e. the system reaches capacity), and produce a decline in throughput with corresponding levels of slow speed. At this stage, the traffic is showing a degree of instability.

Severe Congestion: At this part of the speed/flow curve, there is a noticeable deterioration in traffic speed and its corresponding level of flow.

Although measuring capacity under queue discharge conditions would give values lower than those obtained from the unstable state of traffic, Hounsell et al (1994) comment that this approach has the advantage of conforming to the conventional definition of capacity (Hounsell et al, 1994).

The queue discharge phase of the speed/flow curve has been examined to understand the onset of flow breakdown, and adopted to define traffic congestion in the context of this research.

3.4. Factors which affect motorway capacity

. The definition of capacity given in the HCM is believed to be widely accepted in transport studies. With this definition, it is clear that a number of factors may affect capacity on any given day. These factors are described in the subsequent sub-sections.

3.4.1. Common Factors

This section identifies various factors which may affect the capacity of a motorway.

Physical Features of the Carriageway

These do not change unless the geometric design of the highway changes and include:

Lane widths and road furniture: Research has shown that capacity is dependent on lane widths and road furniture (Slinn, 2005). The HCM also summarises adjustment factors for the maximum flow per lane, indicating a decrease in traffic flow as a result of narrowing lanes and reduction in distance between the driver and road furniture(s) (e.g. safety barriers, structures).

Road geometry/gradient: Similarly, the road geometry/gradient can also have an effect on traffic flow. The HCM suggests that traffic flow tends to decrease with increases in uphill gradient.

Merge-type: Merge-type may also influence capacity, as some merges will result in more driver interaction, which may lead to a reduction in merge capacity of a given motorway section.

Traffic Conditions

These are determined by different elements and include:

Traffic Demand: Flow-breakdown may be anticipated when the level of traffic demand exceeds the capacity of the section being considered as the road will no longer be able to accommodate the traffic. The on-ramp traffic demand may also affect the capacity of a merging section.

Traffic Composition: Traffic composition, such as the percentage of heavy goods vehicles (HGVs) may also affect the capacity of the roads due to their physical size and difference in driving performance when compared to passenger cars. For example, HGVs may not be able to maintain their speed alongside passenger cars when there is a change in the gradient of the road.

Day-types and/or Special Events: Change in traffic conditions may be observed according to day-types (e.g. weekdays and weekends) and in the case of a “special event” (e.g. a traffic incident) occurring which can affect capacity.

Ambient Road Conditions

Ambient road conditions include for example visibility, road surface conditions, temperature and wind and are affected by:

Weather: Research based on empirical data have shown that adverse weather conditions have a negative impact on traffic speeds and contribute to an increase in levels of congestion (Edwards, 1999; Agarwal et al, 2005). For example, severe weather conditions such as heavy precipitation and strong winds may reduce capacity as they cause poor driving conditions (reduction in visibility, increase in headways, etc.).

An analysis undertaken by Chung concluded that a drop in capacity between 4 and 7% was observed during light rain and up to 14% in heavy road conditions. The study also showed a reduction in capacity due to different daylight conditions between the winter and summer periods (Chung et al, 2006). However, the literatures reviewed identified that studies in this area are limited, which may be due to weather information, which is local to the site being investigated, not being readily available and/or easy to collect.

Seasonality/Time of day: Seasonality and time of day may also affect the capacity of the road; e.g. the position of the sun may cause glare and hinder the visibility of drivers. The ATM 12 month report has also indicated a trend whereby traffic demand tends to be greater during the summer period than the winter period (Sultan et al, 2008).

Driver Behaviour

A driver's performance and/or attitude towards driving may vary from one individual to another, and could also be dependent on the time of day. Factors such as the length of the journey, time of travel, familiarity with the road, mood, and driver behaviour (aggressive/defensive) may affect the interaction between vehicles and the capacity of the road (Brackstone et al, 2002; Lewis-Evans et al, 2011; Heslop et al, 2014). The impact of these factors require microscopic analysis which is outside the scope of this study and therefore has not been considered, however, has been accounted for through a user consultation survey. The results of the user consultation exercise are presented later in Section 6.6 and has been examined to support the findings from the traffic data analysis carried out throughout this research.

3.4.2. Factors Unique to Smart Motorways

As mentioned in Section 1.2, the following key features were introduced on the M42 Smart Motorways section as part of the HSR operation:

- Use of the hard shoulder as a running lane (HSR)
- Variable Mandatory Speed Limits (VMSL)

- Full street-lighting⁴
- Emergency Refuge Areas (ERAs)

DMRB Volume 6 Section 1 (TD27/05) Clause 4.5.1 identifies the hard shoulder as an area adjacent to the nearside of the carriageway to stop in the event of an emergency, which also provides access for emergency services and road space under temporary traffic management.

Under HSR operation, the existing roads have been modified to accommodate the hard shoulder as an additional running lane and as a result, lane widths have become narrower than the standard 3.65 m width along various lengths of the M42-SM section. In addition, the distance between road users on the hard shoulder and road furniture are reduced, which may also have an effect on reducing the potential capacity of the road when compared to a standard 4 lane motorway.

The ATM 12 month report has indicated that the use of variable mandatory speed limits with HSR have had the effect of increasing observed motorway capacity as it helps to harmonise speed and prevent the occurrence of flow-breakdown, i.e. minimising driver conflicts (Sultan et al, 2009). This is one of the key differences as flow breakdown on no-VMSL is considered to propagate from the offside lane with the onset of stop-start conditions (Kerner, 2004).

3.5. Summary

This chapter summarises the literature review of the various concepts of capacity, how highway capacity is measured, and to identify a definition that can be applied to this research.

⁴ Full street lighting was introduced along the M42-ATM section as part of the pilot scheme. However, this is not anticipated to be mandatory on future ATM schemes.

The review identified the lack of European reference in the context of estimating speed/flow and flow/density relationships outside of the US; therefore the Highways Capacity Manual remains to be a reference for many researchers today. The factors affecting motorway capacity within this section will be examined throughout this research, where data is available, to understand its effect on traffic conditions during smart motorway operations.

CHAPTER 4

Data collection and processing

4.1. Introduction

The following sub-sections introduce the different types of traffic data collected for the analysis work carried out within this thesis. The section concludes with a high-level overview of the analysis methodology and data aggregation used within this study.

4.2. Data Collection

As mentioned in the previous chapters, the scope of this study has been limited to existing smart motorway sites on the M42 and M6 in Birmingham, UK where HSR is in operation. Although smart motorways operation is currently in operation on other sections of the Highways England road network, they were not in operation (therefore sufficient data was not available) at the time of this research..

To understand the limitations of these types of operational regimes, the data used within this research has been undertaken on a collective basis and/or a targeted analysis basis depending on the type of study being carried out. Data from each links, within junctions, and at the on-slip and off-slips at each junction has been collected from the following data sources where available.

4.2.1. *MIDAS loop data*

This data has been used as the primary data source for this research. Motorway Incident Detection and Automatic Signalling (MIDAS) loops are induction loops installed primarily to detect changes in traffic conditions. Since 2014, radar-based MIDAS data have also been installed on the motorways to replace the induction loop-based MIDAS data; however, this data has not been used as they were being rolled-out on a trial basis at the time of research.

Where applicable, the loops are placed upstream of overhead gantry signals, so that the appropriate signal settings could be implemented as noted in the Design Manual for Roads and Bridges (DMRB) HD20/05, Cl 3.9 (Highways Agency, 2005). The loops are also typically spaced at 500m intervals (Cl 3.11), with the exception of the M42-SM section where loops were installed at 100m intervals for monitoring and evaluation purposes.

MIDAS loops provide the following data on a lane-by-lane basis at one minute intervals (Highways Agency, 2009e):

Flow	This is the number of vehicles passing over the detector for a given one minute time interval.
Speed	This is the time mean speed of the vehicles that have passed over the detector for a given one minute time interval.
Headway	This is the average time between the vehicles that have passed over the detector for a given one minute time interval.
Occupancy	This is the percentage of time the detector is covered (i.e. occupied) by vehicles for a given one minute time interval.

MIDAS loops also provide vehicle classification data at one minute intervals, based on vehicle lengths. This data is collected across all lanes, and not on a lane-by-lane basis (i.e. the data does return HGV counts for each individual lane, and only reports the total number of HGVs at that point of the carriageway).

MIDAS loop data (both induction loop and radar-based) is collated into a daily Traffic Counting Data (TCD) file for each of Highways England's Regional Control Offices (CO). This data is uploaded to a database website, <http://www.midas-data.org.uk/>, and was downloaded by the researcher (with an approved login), on a daily basis. The method of data extraction is later described in Section 4.3.

4.2.2. Individual Vehicle Data

Individual Vehicle Data (IVD) has also been collected from a number of sites along the M42-SM section on a selective basis. IVD is essentially MIDAS data in its raw form, and provides records of vehicle speeds, lengths, headway and time of arrival of every vehicle that passes over the detector site for each lane (Sultan et al, 2008).

IVD is not available from the MIDAS website described in Section 4.2.1, and cannot be collected remotely. This data was collected by connecting a laptop into the roadside cabinets; therefore the researcher gained approval from the Highways Agency to acquire this data, and laptops were installed to the relevant roadside cabinets by Mott MacDonald's contractor who had been trained carry out this work. Data was downloaded from these laptops and issued to the researcher on a weekly basis. IVD has not been generally collected, unless considered necessary, due to safety and cost implications associated with its collection method as it requires operators to work adjacent to the live traffic lane and install laptops in the roadside cabinets for the data to be downloaded.

4.2.3. *HALOGEN Data*

The Highways Agency Logging Environment (HALOGEN) Services provides a facility for Highways England to collect, store and disseminate the Highways Agency Traffic Management Systems (HATMS) data (MCH1681, 2008). This data is collected for each of the Regional COs and information such as VMS settings, signal settings, device setting requests and equipment faults are recorded within the HALOGEN database.

Similar to the MIDAS data, this data is available from a website (<https://halogenonline.dft.gov.uk>) and downloaded by the researcher using an approved login. Sign and signal settings data was obtained from the HALOGEN Control Office Base System (COBS) signal and sign setting records to identify HS opening times and messages displayed on the VMS signs over the study period.

4.2.4. *Video data*

Video footage was collected for the M42-SM and M6 sections for the analysis of TJR which is discussed later in CHAPTER 6. CCTV footage was collected at the merge, diverge and within the junction of the TJR section and along the smart motorway section. This data was obtained by the researcher, through application an application form approved by the Highways Agency Project Sponsor, to request the CCTV footage captured at the Regional Control Centres to be copied on to a DVD.

4.3. Data processing

As mentioned in Section 4.2.1, MIDAS loop data is collated into a daily Traffic Counting Data (TCD) file for each of Highways England's Regional Control Offices (CO). The data is stored in binary form in accordance with the data structure specified within TR2144 (Highways Agency, 2009e). Bespoke macros using Microsoft Excel were developed throughout the course of the research to extract collate the data required (see Appendix A: Sample of Traffic Data Analysis Macro).

The datasets used within this thesis were subjected to a filtration process to remove the following periods:

- Periods with data errors
- Public holidays and special events
- non-HSR operation due to technical faults
- Accident/incidents

The filtration was carried out as follows:

Step 0: Split the dataset in accordance with day-types

The analysis adopted the methodology set in the ATM 12 month report and was classified in accordance with their day-types:

- Mondays
- Tuesdays, Wednesdays and Thursdays [TWT]
- Fridays
- Weekends

Step 1: Remove periods with data errors

The TCD sometimes show a '255', which represents "No Data" (Highways Agency, 2009e). This data occurs in some instances when MIDAS loops are switched-off during roadworks, or an interruption occurred due to a traffic incident. This data was removed from the dataset at one-minute intervals.

Step 2: Remove public holidays and special events from the dataset

Traffic patterns change during public holidays and special events (e.g. events at the NEC, football matches) and do not represent typical traffic conditions. Public holidays were removed from the dataset on a daily basis and special events were removed on a at 30 minute intervals.

The special events were identified by:

- Firstly examining and the traffic flow and average journey time profiles to identify the date and time periods when traffic conditions which were not in line with the general traffic trends within the dataset
- Using the sign and signal records obtained by Halogen and other data sources (e.g. NEC website, football fixtures), to understand if any events were in the region which would have contributed to the unusual traffic condition.

•Stage 3: Remove periods where HSR was not in operation due to technical faults

This was again carried out at 30 min intervals. The information on HSR operation was obtained by processing the Halogen log, which records the timestamps of when the speed limit signals were set.

The researcher was also informed by the HA Project Sponsor when HSR was not in operation due to technical faults (e.g. in 2011, there was a period when the M6 could not use their technical equipment due to cable thefts).

•Stage 4: Remove Accidents, incidents and roadworks

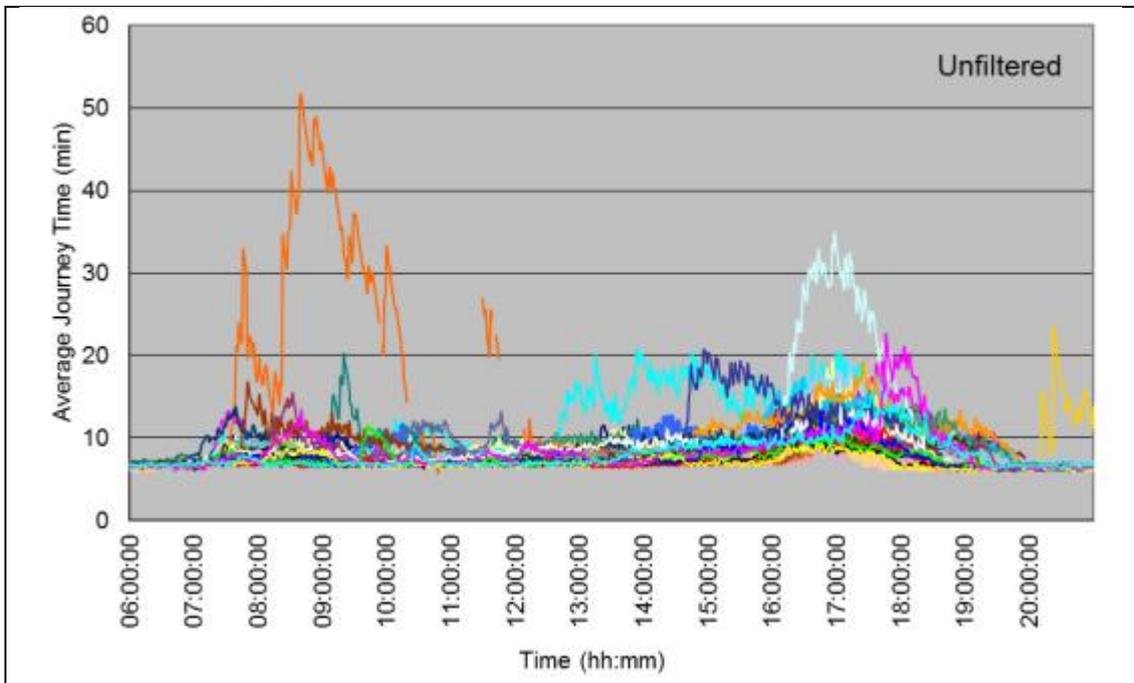
The Halogen data (sign and signal), spatio-temporal plots of flow and speed along the scheme extents and traffic summary reports obtained from the National Traffic Control Centre (NTCC) were used to understand when accidents, incidents and major road works (and their duration) were in place during the study periods.

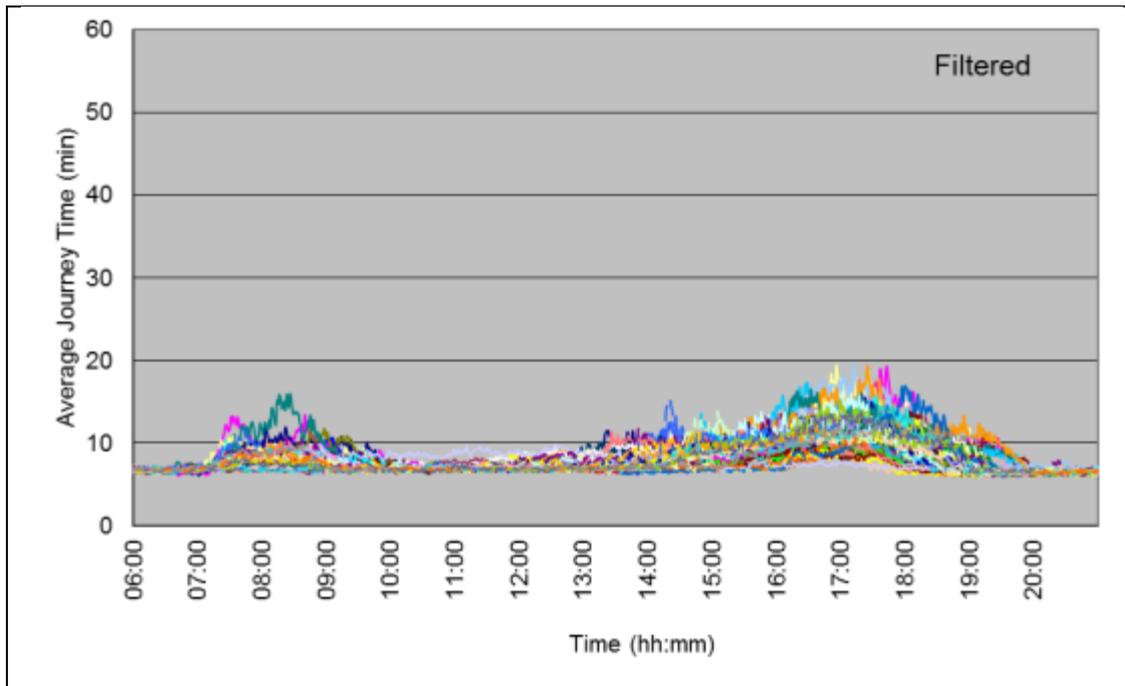
A major incident was identified through the Halogen logs, however, was also observed through the traffic and average journey time plots as a sudden drop in traffic throughput and speeds, and increase in

average journey times were observed from the dataset.

The above filtration process was adopted for this research to represent the ‘true’ impact of smart motorway operations. It should be noted that other users may choose to not filter some of the data depending on their assessment work (e.g. if we want to understand traffic conditions during roadworks, then we would look at periods when roadworks are in place and leave it in the dataset). Figure 22 shows an example of how the dataset looks before and after it is subject to an incident filter.

Figure 22: Example of filtered and non-filtered data





Note: Above shows non-filtered data, below shows data following the application of an incident filter.

Data was collected upstream, downstream and slip-road data, to understand whether the observations made during the analysis are specific to that sign or a result of generalised traffic conditions. Hall et al (1986) also suggest that there are advantages into looking at traffic data on individual days, to firstly identify trends/ideas of the behaviour of each variable in which a collective data cannot provide. This also enables the transition point between free-flow and congestion conditions to be identified. Therefore this research includes a 'Capacity Study' (CHAPTER 8) which has collected data using a selective approach, and the Through Junction Running (CHAPTER 6) and lane utilisation (CHAPTER 9) study which has collected data using a collective approach to assess the observed traffic conditions.

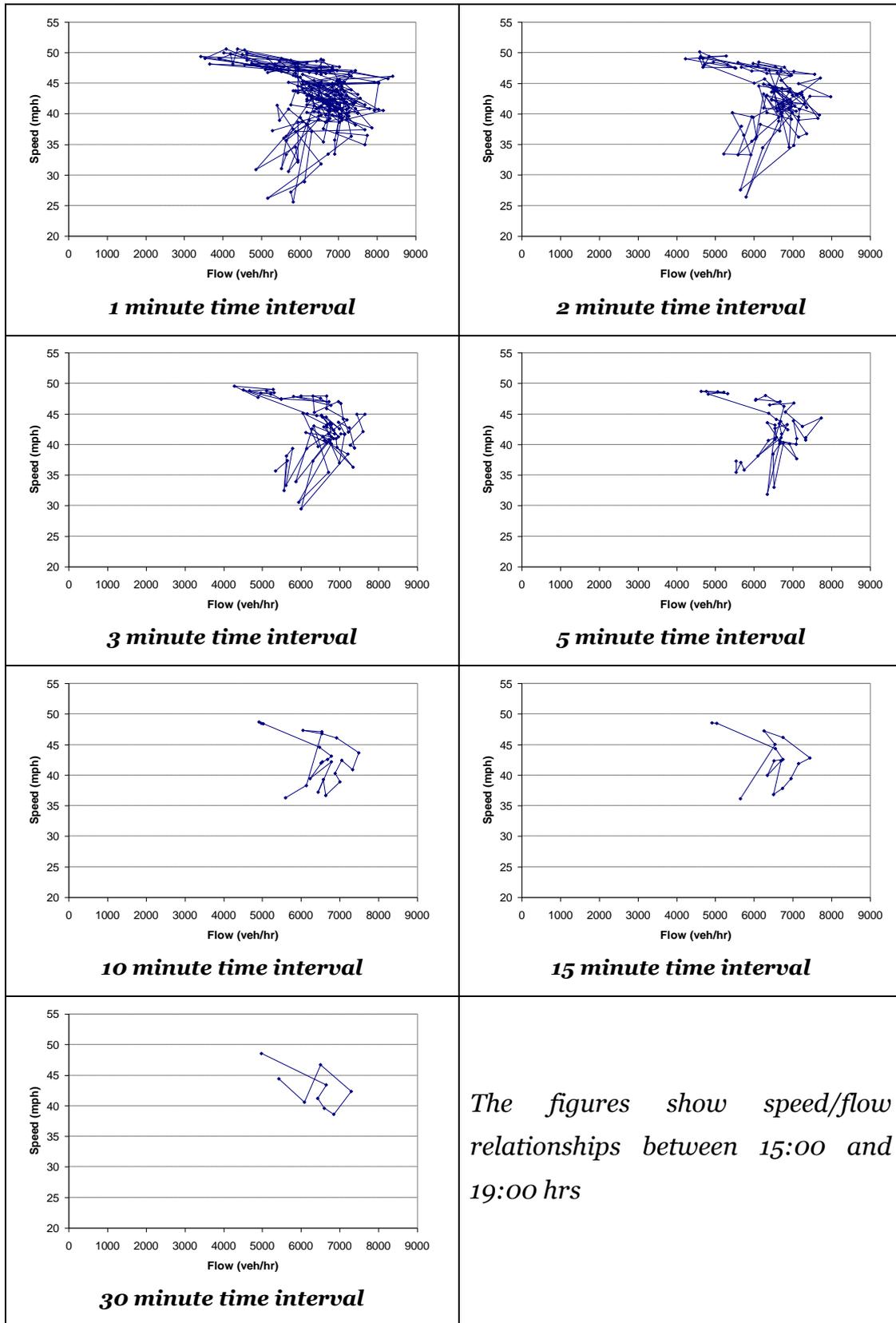
4.4. Data Aggregation

Traffic data at flow-breakdown points of smart motorway sites are required to be collected and processed to understand the factors which affect the performance of this type of operational regime. As mentioned earlier, MIDAS data provides data on a minute-by-minute basis. However, using such a small time interval for data aggregation poses an issue due to the large variability in the flow values between consecutive minutes. Hall et al (2009) suggest that the maximum traffic flows measured at short time intervals may therefore be unsustainable, and that the concept of 'road capacity' is an average figure. Similarly, using longer time intervals (e.g. over 60 minutes) to aggregate the data would not be able to capture the detailed changes in traffic conditions effectively, thus making it difficult to carry out a robust analysis. There is therefore a need to establish the time interval to be adopted for such study.

To determine the appropriate aggregation interval to estimate capacity, a dedicated assessment has been carried out. As discussed in CHAPTER 3, capacity indicates the maximum possible traffic flow which can be accommodated and sustained by the section of road being considered; hence it can be visualised as the maximum flow observed from a speed/flow curve. This was done by evaluating the maximum flow observed on each capacity day at different time intervals, and carrying out qualitative and quantitative analyses to identify the suitable time interval to be used.

Figure 23 shows the speed/flow relationship on one of the capacity days identified at different time intervals. It is clear that with intervals longer than 3 minutes, the speed/flow relationship starts to lose its parabolic shape. This indicates that by considering intervals of 5 minutes and longer, the observed average speed becomes a function of demand and capacity rather than a representation of dynamic of traffic.

Figure 23: Speed/Flow Plots at Different Time Intervals (01.11.2009)



The figures show speed/flow relationships between 15:00 and 19:00 hrs

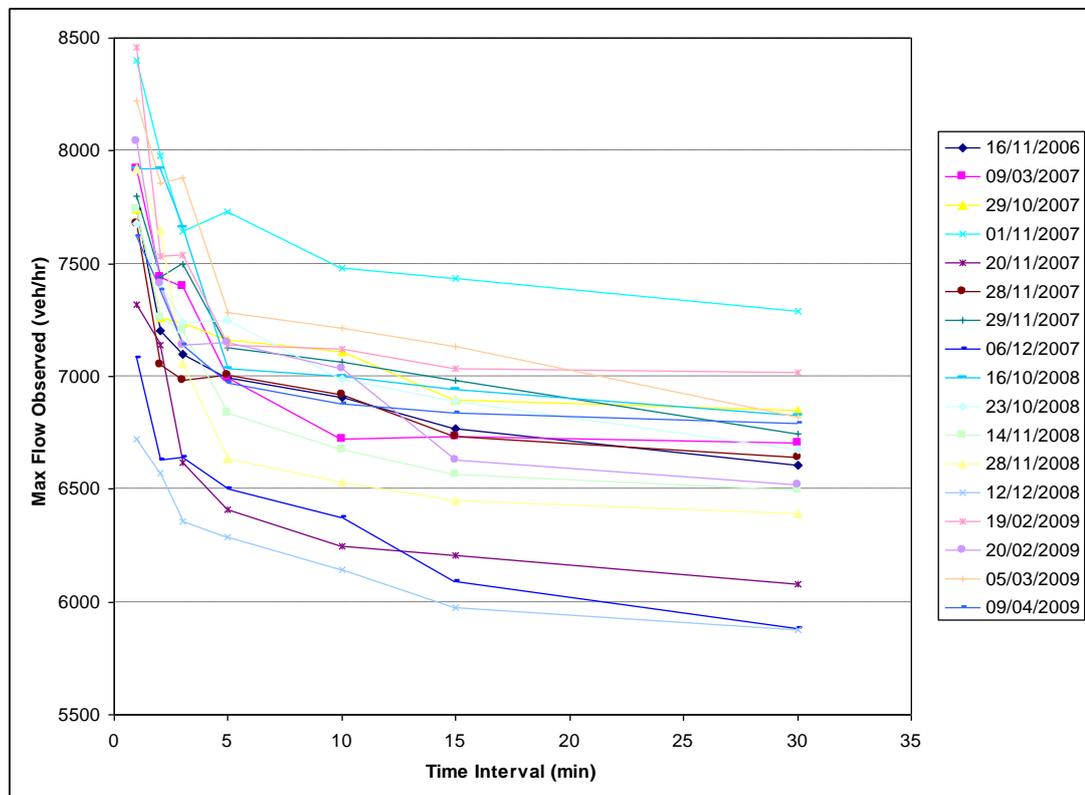
As identified in CHAPTER 3, the capacity should correspond to a flow which can be maintained for a reasonable period of time.

Figure 23 shows that at smaller time intervals (i.e. 1, 2 and 3 minutes), the data is very scattered and the maximum flows observed are not necessarily sustainable (i.e. they are a temporary occurrence and take the maximum of a random variable instead of an average). Therefore from this observation, it may be concluded that these time intervals are too short and not suitable for the capacity analysis, as the observed maximum flows would “over-estimate” capacity.

Figure 24 shows the maximum observed traffic flows for each capacity day at different time aggregation intervals for the period 1st March and 31st August 2007. The data presented shows a big drop in the observed maximum flow between 1 and 5 minute time intervals, which supports the conclusion obtained from

However, for intervals longer than or equal to 5 minutes, the decline in maximum flow is much less which indicates more stable traffic flow. It should be noted that with very long time intervals the result will underestimate capacity.

Figure 24: Maximum Throughput Observed vs. Time Interval (Capacity Days)



The data presented in Figure 24 shows that there is a big drop in the observed maximum flow between 1 and 5 minute time intervals, which supports the conclusion obtained from

Figure 23. However, for intervals longer than or equal to 5 minutes, the decline in maximum flow is much less which indicates more stable traffic flow. It should be noted that with very long time intervals the result will underestimate capacity.

The HCM 2000 identifies 15 minutes as the time period used in most capacity analyses as it is considered to be the appropriate interval during which stable flow exists. However, adopting the use of a shorter time interval (e.g. 5 minutes) as a part of this capacity analysis was found to be a viable alternative.

A statistical analysis was undertaken to inform the decision on a suitable time interval. Both F-tests and paired t-tests were performed to the 5% significance level, and results are as summarised in Table 3⁵.

Table 3: Statistical Test of Maximum Observed Flow (5 min vs. 15 min)

	<i>time interval</i>	
	<i>5 min</i>	<i>15 min</i>
Mean Observed Flow (veh/hr)	6972	6723
Maximum Observed Flow (veh/hr)	7728	7432
Standard Deviation	354	379
F - test	0.79	
paired t - test	0	

⁵ Both F-test and t-test results will show a value less than 0.05 when the difference between the two samples are significant

The F-test assesses the difference in the variability of the maximum observed 5 minute flow and 15 minute flow. Results show that the difference in variance is statistically insignificant between the maximum 5 minute and 15 minute flows observed, which suggests little difference between the two intervals in terms of variability.

The paired t-test was undertaken to examine the difference in maximum observed flows between the 5 minute and 15 minute periods. As expected, results have shown that there was a significant reduction in the observed maximum flows in the 15 minute period when compared to the 5 minute time interval.

The above results show that the maximum flow obtained from the 15 minute interval has similar variability to that of the 5 minute interval. However, the test has shown that the use of the 5 minute time interval will result in higher flow levels compared to 15 minutes. In this study the aim is to estimate the level of capacity that can be sustained, and not the absolute maximum flow rate observed. Therefore, the 15 minute time interval is deemed to be more appropriate for this study. This time interval also maintains consistency with the HCM Manual, which is recognised internationally, and gives a better representation of the level of capacity that can be sustained.

4.5. Summary

This section provided an overview of the types of traffic data available and collected for the analysis work carried out within this thesis. A number of bespoke Excel macros were produced to carry out the analysis specific to this research work.

The section concludes with a high-level overview of the analysis methodology and data aggregation used within this study. MIDAS data provides data on a minute-by-minute basis; however, using such a small time interval for data aggregation poses an issue due to the large variability in the flow values between consecutive minutes. Similarly, using longer time intervals (e.g. over 60 minutes) to aggregate the data would not be able to capture the detailed changes in traffic conditions effectively, thus making it difficult to carry out a robust analysis.

Following the analysis, a 15 minute time interval was deemed to be most appropriate for this study as it maintains consistency with the international standard and gives a better representation of the level of capacity that can be sustained. This time interval has been adopted throughout the research work.

CHAPTER 5

Operational impact of HSR in the UK

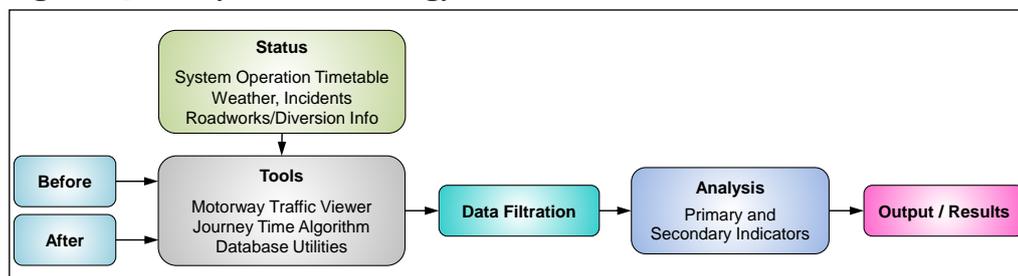
5.1. Introduction

As mentioned earlier in Section 2.3, the performance of smart motorways ('after' case) was compared with non-managed conditions ('before' case) over a comparable period of time throughout the scheme extent to understand the impact of smart motorways. This section provides a summary of the high-level analysis, carried out by the researcher, to understand the impact of existing smart motorways in Birmingham, UK.

5.2. Analysis methodology

The high-level overview of the analysis methodology is presented in Figure 25.

Figure 25: Analysis methodology



Note that HSR50 represented the before case for the HSR60 assessment on the M42-MM.

5.2.1. Sample size and available dataset

The assessments carried out in this chapter followed the data filtration process described in Section 4.3. The sample size and dataset for the data used within this chapter is summarised in Table 10.

Table 4: Sample size and available dataset, M42 Junction 5 southbound

a) M42-MM (HSR50)

	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	48	67%	67%	71%	71%	75%	69%
	TWT	143	65%	68%	69%	66%	69%	64%
	Fri	48	65%	52%	71%	67%	69%	67%
After	Mon	48	71%	81%	71%	73%	75%	56%
	TWT	142	85%	79%	65%	84%	78%	49%
	Fri	47	79%	60%	53%	79%	62%	47%

b) M42-MM (HSR60)

	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	26	88%	93%	92%	80%	85%	70%
	TWT	75	90%	89%	79%	84%	85%	60%
	Fri	26	89%	73%	69%	85%	71%	59%
After	Mon	26	82%	83%	76%	78%	83%	80%
	TWT	79	87%	84%	75%	87%	87%	74%
	Fri	25	73%	73%	71%	91%	87%	73%

c) BBMM Phase 1 (HSR sections)

	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	12	48%	70%	66%	47%	64%	73%
	TWT	36	81%	81%	71%	76%	88%	64%
	Fri	12	88%	75%	73%	79%	78%	63%
After	Mon	14	61%	64%	74%	78%	70%	75%
	TWT	39	83%	89%	82%	95%	96%	90%
	Fri	13	84%	75%	66%	92%	8%	68%

c) BBMM Phase 1 (CM sections)

	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	12	62%	74%	73%	58%	71%	73%
	TWT	36	88%	86%	74%	74%	87%	60%
	Fri	12	92%	83%	74%	79%	80%	65%
After	Mon	14	61%	71%	74%	78%	70%	75%
	TWT	39	87%	94%	84%	95%	95%	89%
	Fri	13	84%	75%	66%	85%	85%	68%

e) BBMM Phase 2

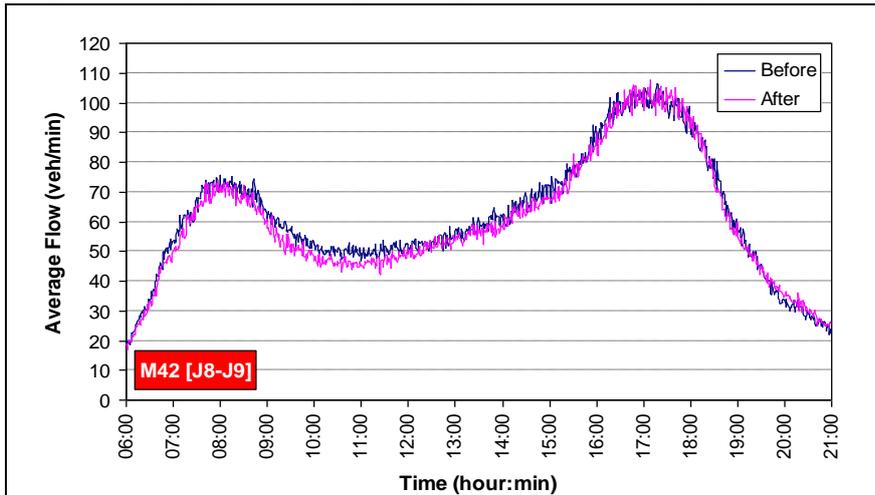
	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	26	77%	75%	70%	73%	65%	71%
	TWT	79	83%	73%	76%	79%	81%	85%
	Fri	26	87%	75%	64%	82%	85%	89%
After	Mon	26	64%	47%	60%	58%	56%	64%
	TWT	78	87%	77%	73%	79%	81%	87%
	Fri	27	84%	57%	58%	70%	57%	80%

5.3. Traffic demand and throughput

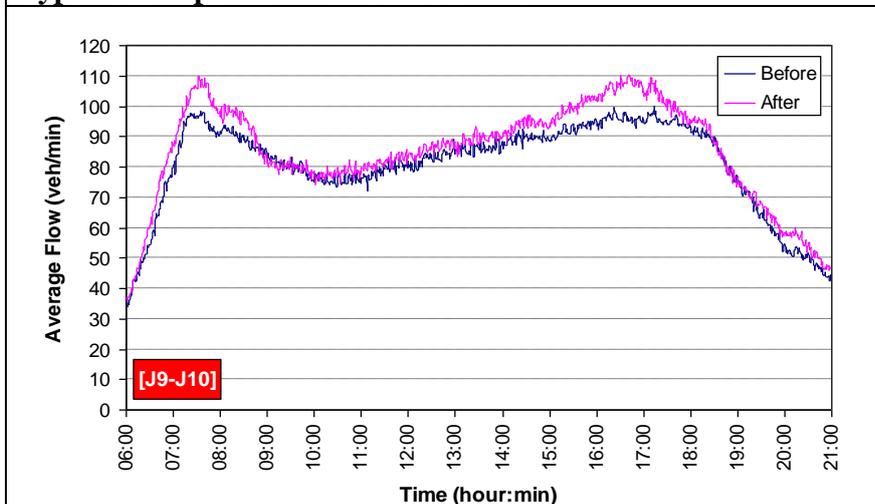
5.3.1. Traffic demand

To directly compare the after case with the before case, it is ideal for the traffic demand in the two cases to be similar. Figure 26 presents the typical average flow profiles on the BBMM Phases 1 and 2 for the [Tuesdays, Wednesdays and Thursdays (TWT)] day-type.

Figure 26: Typical average flow profiles at BBMM, [TWT]



Typical flow profile at BBMM Phase 1



Typical flow profile at BBMM Phase 2

In general, the average traffic flow profiles were similar in shape in the before and after cases at all sites. However, due to the long time period between the study periods, a statistically significant increase in traffic demand was observed for the M42-MM HSR50 and BBMM Phase 2 assessments. Alternative study periods were investigated but due to the availability of traffic data in the before case, these could not be used.

5.3.2. Traffic throughput

The 15 minute maximum flow, i.e., the number of vehicles observed passing a particular point on the motorway over a 15 minute period, was studied on a link-by-link basis to understand the impact of the assessed operational regimes on the motorway capacity. Table 5 shows that statistically significant increases in maximum throughput were observed on most links.

Table 5: 15 minute maximum flows

Scheme	Northbound				Southbound			
	M42-MM (HSR50)	M42-MM (HSR60)	BBMM Phase 1	BBMM Phase 2	M42-MM (HSR50)	M42-MM (HSR60)	BBMM Phase 1	BBMM Phase 2
Before	6199	6489	5987	6282	6177	6452	5223	5825
After	6683	6547	6209	6737	6537	6512	5368	6257
% diff	8%	1%	4%	7%	6%	1%	3%	7%

N.B. The HSR60 case represents changes against an HSR50 case

In addition to the results above, a significant increase in maximum throughput was also observed on a number of M42-MM links following the introduction of BBMM Phase 1.

5.4. Journey time analysis

Table 6 summarises the results from the journey time analysis which was undertaken on a route basis so that the overall impact of the implemented schemes can be understood. Note that CM is in operation on the M42 links between J7 and J9 and M40 between J16 and M42 J3A.

Table 6: Average journey times

Journey Time Route	Northbound		Southbound	
	AM-Peak (06:00 – 11:00 hrs)	PM-Peak period (16:00 – 21:00 hrs)	AM-Peak (06:00 – 11:00 hrs)	PM-Peak period (16:00 – 21:00 hrs)
M42-MM (HSR50): M42 J3A to J7	+ 11% (~1 min 4 sec)	+ 4% (~25 sec)	+11% (~1 min 7 sec)	+ 3% (~22 sec)
M42-MM (HSR60): M42 J3A to J7	- 5% (~30 sec)	- 3% (~23 sec)	- 5% (~36 sec)	- 4% (~27 sec)
BBMM Phase 1 (HSR sections): M40 J16 to M6 J5	- 8% (~1 min 25 sec)	- 5% (~54 sec)	- 3% (~36 sec)	- 6% (~1 min 5 sec)
BBMM Phase 1 (CM section): M40 J16 to M42 J9	- 4% (~35 sec)	- 5% (~47 sec)	- 2% (~17 sec)	- 2% (~22 sec)
BBMM Phase 2: M6 J8 to J10A	+ 4% (~16 sec)	- 8 % (~40 sec)	- 10% (~18 sec)	- 3% (~18 sec)

N.B. The HSR60 case represents changes against an HSR50 case

An increase in average journey times was observed on the M42-MM and BBMM Phase 2 northbound routes; however, this can be attributed to a significant increase in traffic demand between the ‘before’ and ‘after’ cases. In general, average journey times reduced in the after case across all day-types during the AM-Peak and PM-Peak periods. Statistically significant reduction in average journey times were observed on the HSR sections and marginal reduction in average journey times were observed on the CM sections as expected.

The variability of journey times, evaluated as the standard deviation of average journey times, also showed a reduction on all schemes.

Table 7: Change in journey time variability

Scheme name	Change in Journey Time Variability
M42-MM (HSR50)	-22%
M42-MM (HSR60)	-18%
BBMM Phase 1	-14%
BBMM Phase 2	-50%

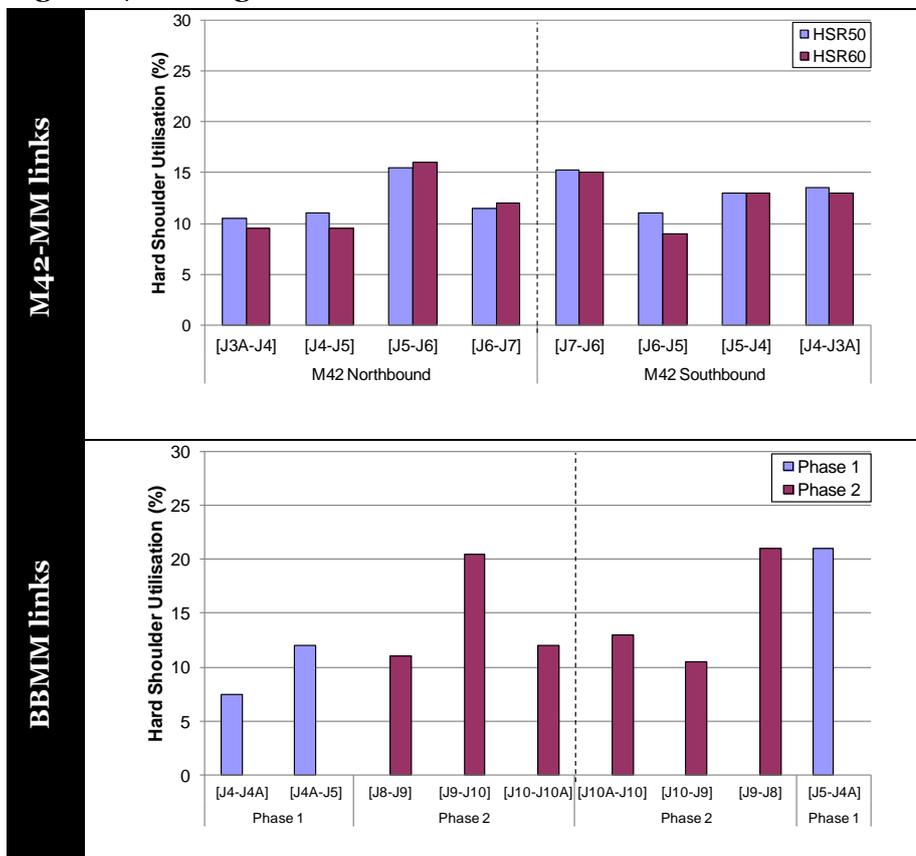
The changes shown for the primary indicators strongly imply that the introduction of smart motorways at these three locations has helped to smooth traffic flow and improve journey time reliability (i.e. predictability). In turn this enables road users travelling on these links to predict their journey times better.

5.5. Hard shoulder utilisation

Hard shoulder utilisation was studied over partial periods of the AM-Peak and PM-Peak at times when HSR is typically in operation. In general, HSR was observed to be in operation for a longer duration at BBMM Phase 2 than on the M42-MM and BBMM Phase 1 sections due to higher peak period traffic flows.

Figure 27 shows that average hard shoulder utilisation was comparable for each scheme at approximately 12% across all day-types, with a few notable exceptions. Average hard shoulder utilisation on the M6 [J5-J4A] southbound, [J9-J8] southbound and [J9-J10] northbound links were higher than other HSR links at approximately 21% across all day-types. It is suggested that this is due to the large volume of traffic that leaves the M6 at these locations. The new road layout and HSR are also helping to smooth this movement.

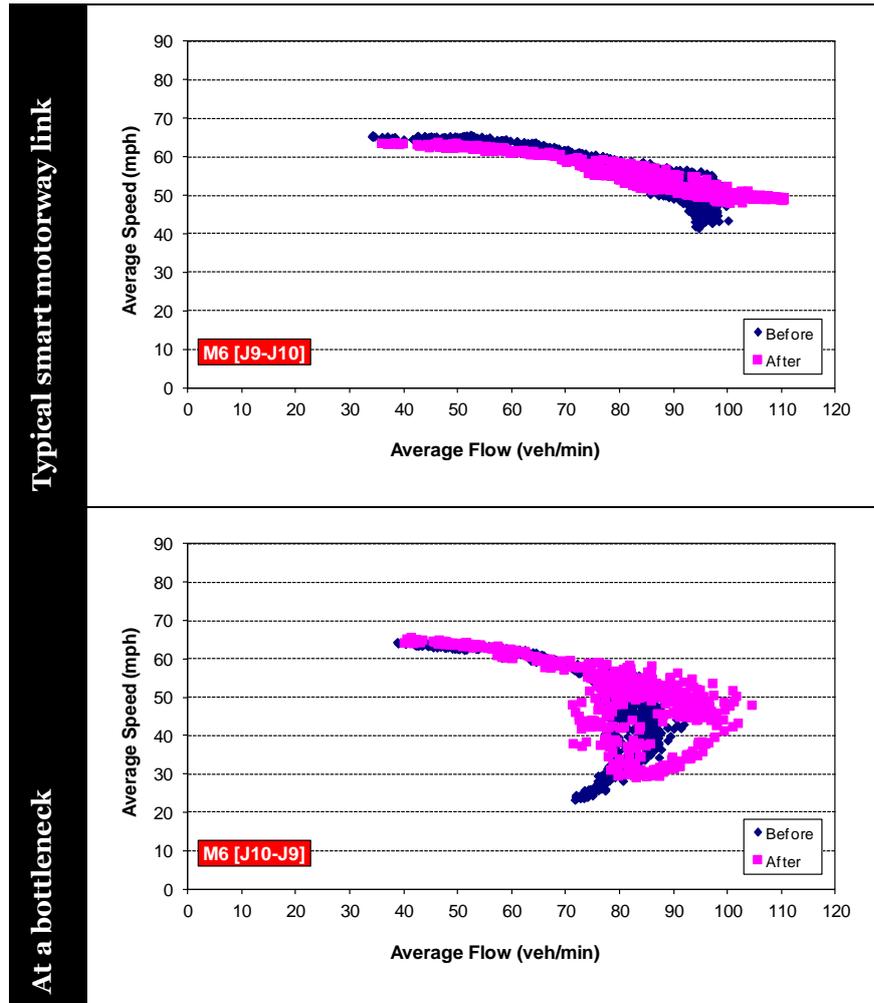
Figure 27: Average hard shoulder utilisation



5.6. Average speed/flow relationships

The average speed/flow relationships were examined to assess the level of service observed on the motorway sections considered. Figure 28 presents typical speed/flow relationship plots for the before and after cases at a bottleneck and on a typical smart motorway link.

Figure 28: Typical average speed/flow plot, before vs. after



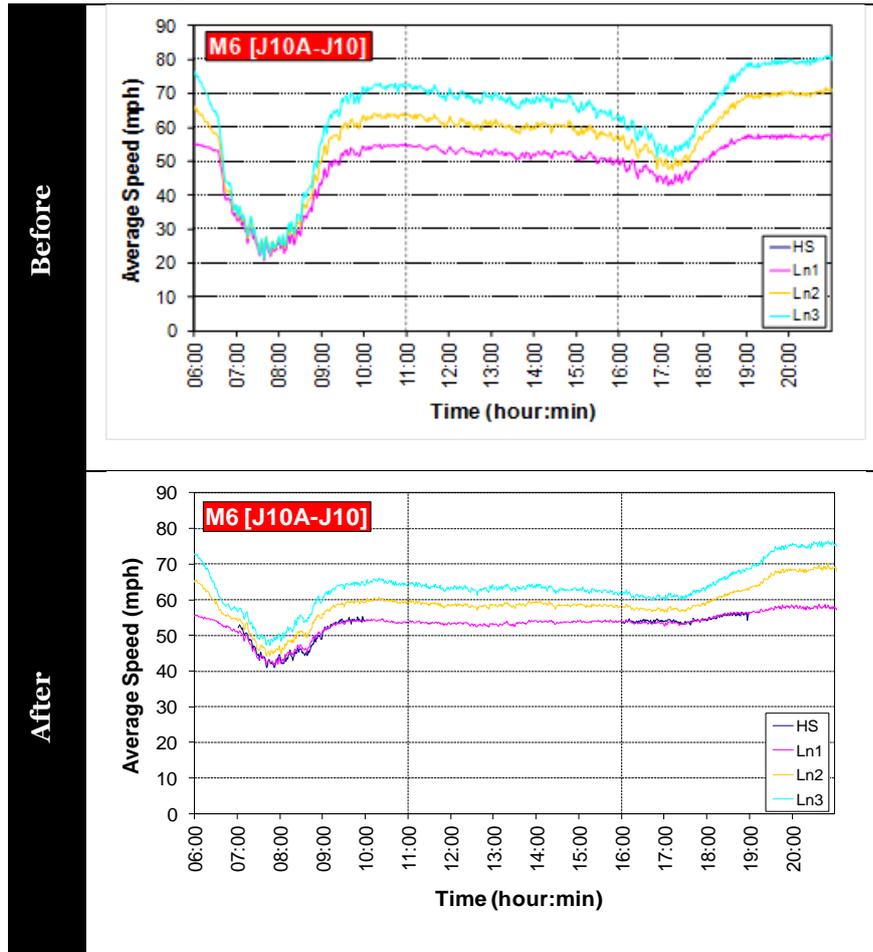
Overall, the speed/flow evaluation indicates that the introduction of smart motorways reduced the occurrence of recurrent severe congestion (i.e. points corresponding to periods of low flow and speed) for most links. Although a statistically significant increase in maximum throughput was observed on the M6 [J4A-J5] northbound and [J10-J9] southbound links, an increase in the number of points corresponding to periods of low speed and low flows (i.e. unstable conditions) were also observed at these locations. It is considered that this observation is due to their downstream links operating as a standard 3 lane motorway; hence acting as a natural bottleneck and causing congestion.

5.7. Average speed profiles and variations in speed

As mentioned in Section 1.2, one of the aims of smart motorways is to smooth traffic flow by setting VMSL during periods of congestion. An indication of whether this has been achieved can be obtained by examining the average speed profiles and difference in average speeds between lanes. Figure 29 presents a typical speed differential between lanes plot before and after smart motorways implementation.

The results show that traffic flow has become smoother since the introduction of smart motorways at existing schemes. The speed profiles show that during the build-up and decay of the peak periods, the change in average traffic speeds is less since the introduction of smart motorways. Average speeds on the most congested links improved on average by 5 mph.

Figure 29: Speed differential between lanes, before vs. after



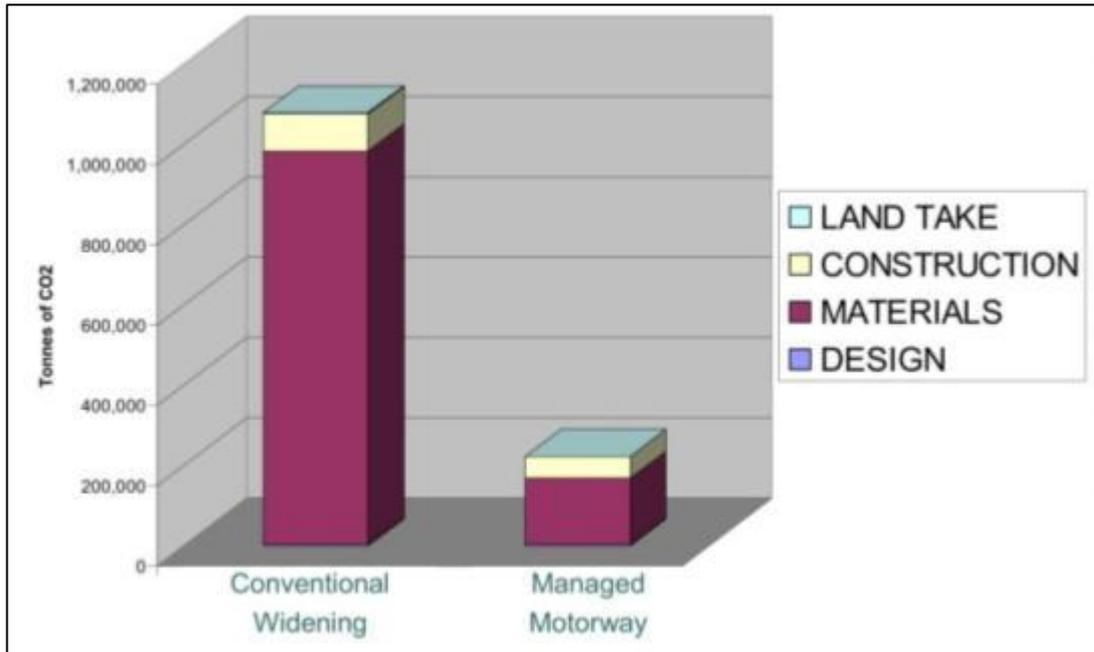
5.8. Safety benefits

A three-year safety report carried out for the M42-MM section demonstrates that the number of Personal Injury Accidents (PIA) and severity of accidents had reduced following the implementation of HSR (Blaney et al, 2011). The monthly average number of accidents reduced from 5.08 accidents per month (non-managed conditions) to 3.17 accidents per month during CM operations and 2.25 accidents per month during HSR operations.

5.9. Environmental benefits

Research conducted by Holt in 2009 demonstrated that over a carriageway length of 546 km⁶, HSR schemes could reduce approximately 850,000 tonnes of carbon when compared to conventional road widening scheme as shown in Figure 30 (Holt et al, 2009).

Figure 30: CO2 Impact of motorway widening vs. Smart motorways



Source: Holt et al (2009)

Although the research undertaken to date demonstrates an improvement in safety and environmental aspects (emissions and noise levels), these benefits were generally associated with the improvements in average speed and speed compliance and therefore has not been addressed as a part of this EngD research.

The key features and observed benefits from a selection of projects are summarised in Table 8 below.

⁶ The 546 km is based on the total length of new HSR schemes which are to be implemented or be in construction by 2015 (as of 2009).

Table 8: Comparison of Smart motorway schemes by country

	UK	Netherlands	Germany	France	US
ERAs	Every 500 – 800 m	Every 750 m	1000 m	Not known	Available, but spacing is not known
Traffic Sensors	MIDAS loops every 500 m (100 m for M42 Pilot project)	Every 500-600 m on main carriageway, every 75 m on the hard shoulder	Every 1000 m	CCTV cameras every 250 m and Video Detection Units	Every 800 m
Lane widths	Standard motorway: 3.65 m HSR sections: Variable across lanes (3.20-3.70 m)	3.60m	Standard motorway: 3.75 m minimum lane width: 3.25m (3.50m for heavy goods vehicles)	Standard motorway: 3.50m HSR sections: 3.00 - 3.20 m	Washington: 3.65 m
Gantry spacing	500 m on M42-MM 800 – 1000 m	700m	1000 m	Not known	Every 800 m
Operating Speed	No-HSR: 70 mph During HSR utilises three speed limits (60 mph, 50 mph and 40 mph)	No-HSR: up to 130 kph (~81mph) for motorways, 100 kph (~62 mph) for national roads During HSR utilises three speed limits (90 kph (56 mph), 70 kph (44 mph) and 50 mph (31 mph))	No-HSR: 120 kph (75 mph) During HSR: between 100 kph (62 mph) and 130 kph (81 mph)	No-HSR: 130 km/h	Reduces either at 10 mph or more commonly, 5 mph intervals
Journey Time improvements	22%	4% (~ 3 minutes/km)	20%	20-50%	Figures not known
Capacity improvements	7-9% (HSR50)	7-22%	25%	7.5 – 10%	Figures not known

Each scheme has also reported an improvement in safety and environmental aspects (emissions and noise levels); however, as discussed earlier, these benefits were generally associated with the improvements in average speed and speed compliance and therefore have not been addressed as a part of this EngD research.

5.10. Challenges within Smart motorways

The HSR schemes studied within this section have shown that this innovative approach of congestion management utilising VMSL and the hard shoulder has provided additional road capacity and improvements in journey times (associated with improvements in traffic speeds) in an effective and efficient manner. Although the evaluation work undertaken to date has led to HSR being introduced to additional sections of roads in the UK, the full potential and limitations of this application are still unknown. The following sub-sections elaborate on key challenges that are to be addressed within future Smart motorway schemes.

5.10.1. Technological Requirements

Smart motorway schemes rely on a wide range of ITS (e.g. gantries, signals, VMS, CCTV) and additional skill and monitoring activities such as the monitoring of traffic flow and speed, clearance of hard shoulder, and incident detection. Such technology introduces additional workload to the traffic control officers as the traffic conditions need to be monitored more regularly to maintain flow and respond effectively in the event of an incident (Simpson et al, 2009).

Technological advances in traffic sensors (e.g. MIDAS loops in the UK) and video technology observed in the French schemes have assisted traffic control officers in the monitoring of HSR operations remotely, without having to look at multiple CCTV monitors constantly. Automated control of VSL have also been introduced in Germany (Mirshashi et al, 2007), and hence the additional advances and flexibility in such ITS technology could assist and bring further benefits to future Smart motorway schemes.

5.10.2. 'Optimal' Operation of HSR schemes

Establishing the appropriate threshold (i.e. optimal algorithm) to trigger the commencement of HSR operation is not an easy task. In the M42 Smart motorways schemes, traffic sensors such as MIDAS loops have enabled traffic officers to measure the changing traffic conditions effectively; however, the flow thresholds introduced were not ideal during the initial operation stages (Simpson et al, 2010).

For the initial Pilot, thresholds for 3L-VMSL (i.e. CM conditions) on the M42 were identified based on historical data from the M42, and the 4L-VMSL thresholds for HSR50 were established based on the M25 Controlled Motorways schemes as there were no predecessors of an OR within the UK which utilised VSL. For HSR operations, the initial thresholds appeared to be too high for the M42 as the traffic demand and compositions varied greatly to that of the M25 CM sites. Since then, HSR trigger levels been revised regularly and with the introduction of BBMM1 and TJR are continued to be monitored for further optimisation of the system. Therefore any changes in trigger levels which may affect the traffic characteristics observed within the analysis work would need to be recognised.

5.10.3. Site Requirements

Although the existing Smart motorway schemes within and outside of the UK have been successfully deployed, it is still unknown whether these solutions were successful given the particular application or site specific characteristics. For example, links within each HSR scheme will inevitably vary in their highway geometry and traffic characteristics (traffic demand, composition and patterns), hence the operation of HSR will need to be dealt with accordingly as the monitoring and evaluation works take place. In the UK, IAN 111/09 is the current standard specifically related to HSR operations, and this document is continuously being revised as the monitoring and evaluation of Smart motorways progresses.

CHAPTER 6

Through Junction Running

6.1. Introduction

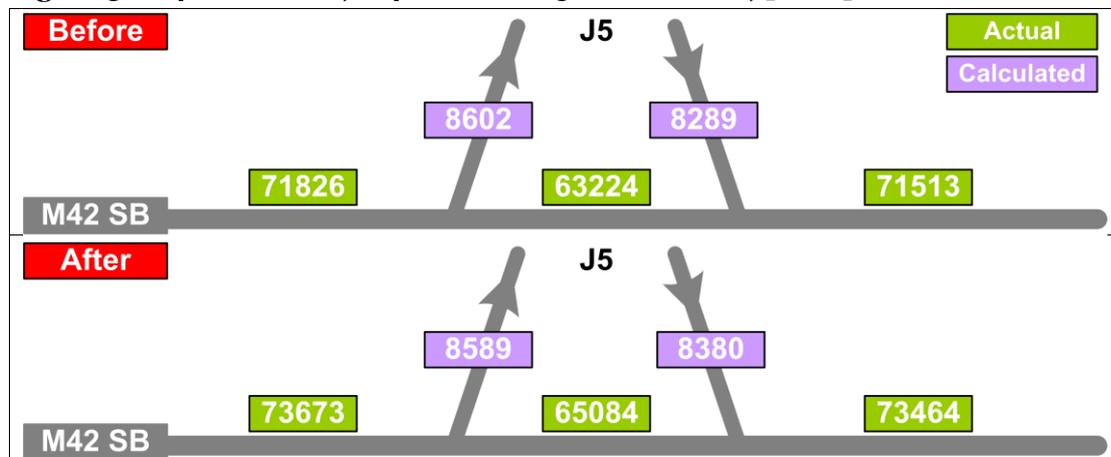
TJR aims to provide benefits over and above those expected with HSR operations, by enabling motorists to drive along the hard shoulder within junctions, i.e. between slip roads, without the need to change lanes. There is a need to understand the operational impact of part-time TJR on the M42-MM section and full-time TJR on the M6 smart motorway section on flow, speed, journey time through the TJR section and driver behaviour at the merge/diverge sections. This will be achieved by addressing the following objectives:

- 1 Evaluating whether TJR leads to an increase in maximum throughput.
- 2 Evaluating whether TJR has an effect on average journey times.
- 3 Determining whether TJR leads to an increase in the utilisation of the hard shoulder.
- 4 Assessing whether there is evidence of lane changing or swooping (lane movements across 2 or more lanes) at the merge/diverge sections due to TJR, and any evidence of drivers being reluctant to cross the diagonal white line marked across the hard shoulder at the beginning of the TJR section.

6.1.1. M42 Junction 5 southbound

TJR was introduced at Junction 5 on the M42 in the southbound direction on the 9th December, 2009. Figure 31 presents the 24 hour traffic flows for the [Tuesday, Wednesday and Thursday (TWT)] day-type at this TJR site. This site was deemed to be suitable as the first TJR site in the UK as approximately 88% of the traffic continues on the main carriageway at this location.

Figure 31: 24 hour flows, M42 Junction 5 Southbound, [TWT]⁷



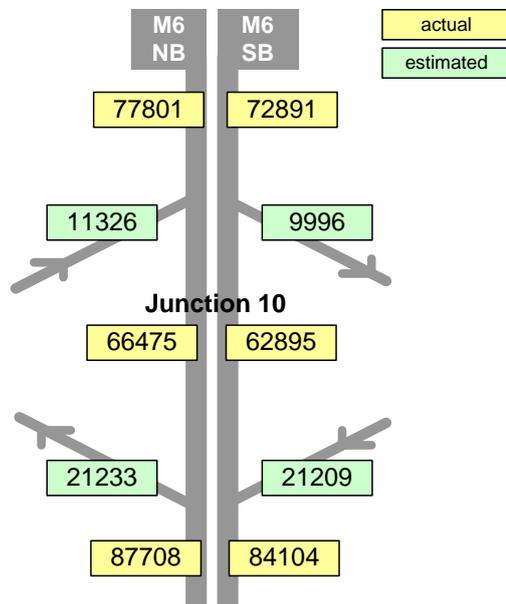
As discussed earlier, TJR operates on a part-time basis (during periods of congestion); i.e. the hard shoulder is opened when HSR becomes operational on its upstream and downstream links. All other links on the M42-MM section are in the lane-gain/lane-drop arrangement at the time of writing.

⁷ The slip-road flows were calculated by obtaining the difference between the main carriageway flows before and after the merge and diverge.

6.1.2. M6 Junction 10 northbound and southbound

TJR was introduced at M6 J10 in the northbound and southbound directions (full time). Similar to the M42 TJR site, the 24 hour traffic flows at M6 J10 for the after case are presented graphically in Figure 32 for the [TWT] day-type. The slip-road flows were calculated by obtaining the difference between the main carriageway flows before and after the merge and diverge. Note that a high volume of traffic was observed joining the M6 southbound.

Figure 32: 24 hour flows, M6 J10, April – September 2011 [TWT]



Within the previous operational regimes, hard shoulder running (HSR) was only permitted between junctions (i.e. in a lane gain/drop arrangement), with motorists having to return to the main carriageway if continuing on the motorway beyond the junction diverge. It was identified that this arrangement may limit the full potential of HSR, particularly at junctions where a low proportion of traffic leaves/joins the motorway.

TJR aims to further improve traffic flow and reduce congestion on the M42-MM section over and above the improvements observed following the introduction of HSR, by enabling motorists to drive along the hard shoulder within junctions (i.e. between slip roads), without the need to change lanes.

6.2. Evaluation method

6.2.1. Analysis methodology

The evaluation approach was to compare traffic conditions on the M42-MM and M6 smart motorway sections during TJR operation with a comparable period of time without TJR. The methodology outlined in Section 5.2 was adopted for this analysis.

6.2.2. Assessment period

The following dates were chosen for the assessment of TJR operations.

Table 9: Assessment periods

	M42 Junction 5 southbound	M6 Junction 10
Before case	1st February 2009 – 31st July 2009	1st April 2008 – 30th September 2008
After case	1st February 2010 – 31st July 2010	1st April 2011 – 30th September 2011

6.2.3. Datasets and Filtration

Table 10 presents the sample size and available dataset used within this CHAPTER 6. As mentioned earlier, TJR at M42 Junction 5 southbound only operates once its upstream (M42 [J6-J5]) and downstream (M42 [J5-J4]) are opened for HSR. Therefore the dataset was initially filtered to only include days where HSR was in operation on the upstream and downstream links. This was done on an AM-Peak (06:00-11:00 hrs) and PM-Peak (16:00-21:00) basis, and is presented as the “days in period” within the table. The “days in period” were subsequently subjected to a filtration process to remove data errors, accident/incident related data, public holiday periods and unusual traffic conditions.

Table 10: Sample size and available dataset, M42 Junction 5 southbound

	Day Type	Days in period		Northbound		
		AM	PM	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	18	21s	84%	90%	88%
	TWT	60	63	95%	93%	82%
	Fri	18	23	100%	71%	60%
After	Mon	11	16	88%	64%	72%
	TWT	45	43	94%	93%	79%
	Fri	14	15	96%	76%	64%

a) M42 Junction 5 southbound

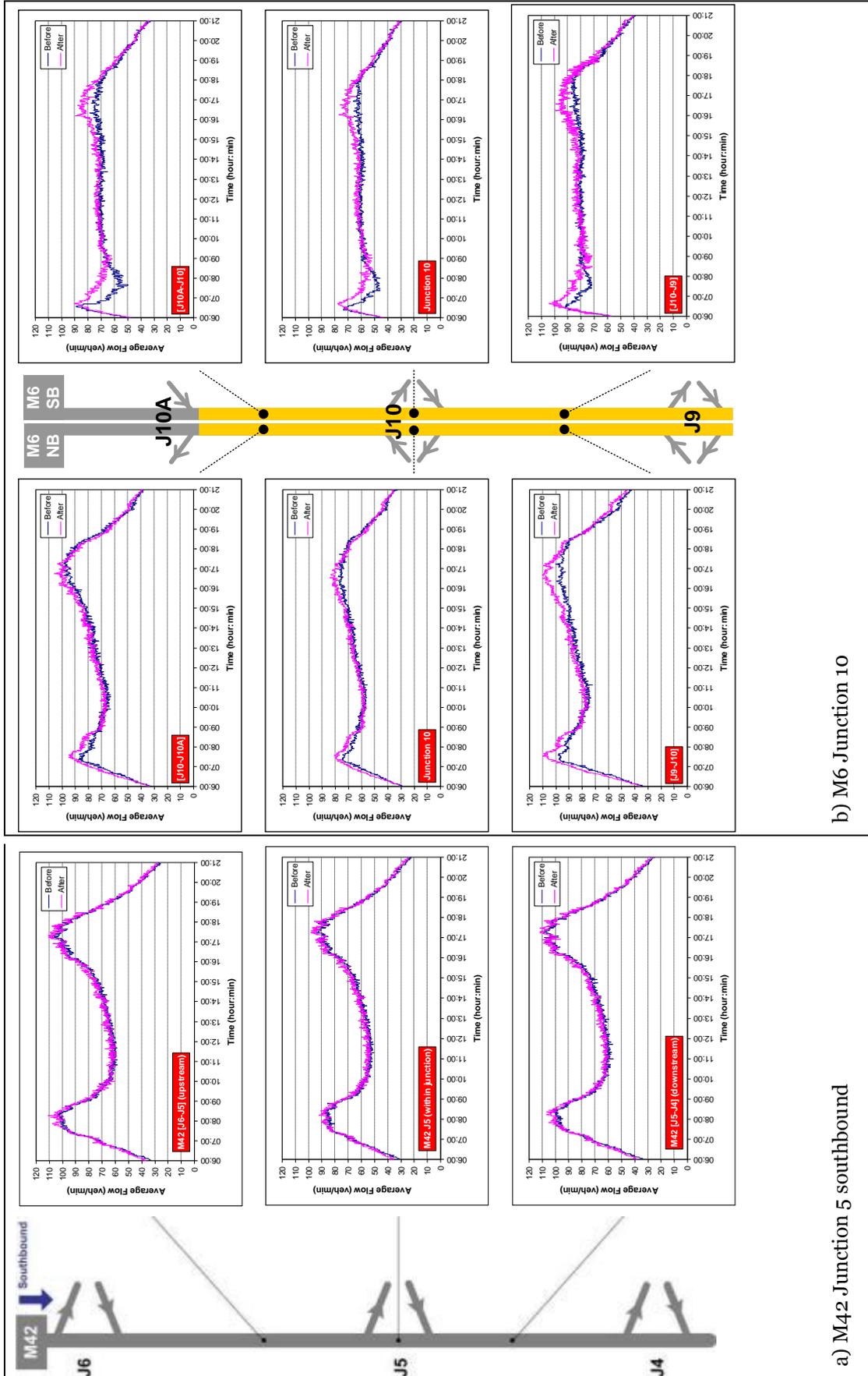
T	Day Type	Days in period	Northbound			Southbound		
			AM-Peak	Inter-Peak	PM-Peak	AM-Peak	Inter-Peak	PM-Peak
Before	Mon	26	77%	75%	70%	73%	65%	71%
	TWT	79	83%	73%	76%	79%	81%	85%
	Fri	26	87%	75%	64%	82%	85%	89%
After	Mon	26	64%	47%	60%	58%	56%	64%
	TWT	78	87%	77%	73%	79%	81%	87%
	Fri	27	84%	57%	58%	70%	57%	80%

b) M6 Junction 10

6.3. Traffic Demand and Throughput

As mentioned in Section 2.3, it is beneficial for the traffic demand to be similar in both cases to enable a direct comparison of the conditions in the before and after cases to be made. Figure 33 shows the average daily traffic flow profiles at the two TJR sites for the [TWT] day-type.

Figure 33: Average Flow Profiles [TWT]



The flow profiles on the M42 section show that there has been a small increase in traffic flow throughout the peak periods (06:00 – 21:00 hrs) for all day-types when compared to the before case; however, the flow profiles in the after case are similar in shape to those in the before case, indicating that there was no noticeable change in travel patterns between the two cases.

Although the average flow profiles on the M6 are similar in shape for the before and after cases, traffic flows were noticeably higher in the after case throughout the peak periods (06:00 – 21:00) on all links for all day-types. In addition, flow profiles along on this section did not appear to be typical of those observed on the M42 and other managed sections on the M6 where clear AM-Peak and PM-Peak periods are observed on the [Mondays] and [TWT] day-types.

6.3.1. 24 hour and 5 hour traffic flows

Table 11 shows the average 24 hour and 5 hour traffic flows on each link for [TWT] for the before and after cases. A statistical test (Student's t-test) has been undertaken (to the 5% significance level) to determine whether differences in traffic flows between the two cases are due to random fluctuations within the dataset or representative of statistically significant changes. To simplify the presentation of the results, the actual probability values have been replaced by an indicator. The indicator gives a value of zero when the difference in mean flow between the before and after cases are not statistically significant. Cells are highlighted in yellow and the indicator shows a value of 1 when the average demand increased by a statistically significant amount. Note that none of the results showed a decrease in flow over the periods measured.

Table 11: Comparison of Traffic Demand, Before vs. After [TWT]

Link	AM-Peak (veh/5 hrs)				Inter-Peak (veh/5 hrs)				PM-Peak (veh/5 hrs)				24 hours (veh)			
	[06:00-11:00]				[11:00-16:00]				[16:00-21:00]							
	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test
[J6-J5]	22522	23014	2%	0	20391	20942	3%	1	21789	22314	2%	0	71826	73826	3%	0
Junction 5	19618	20102	2%	0	18008	18591	3%	1	19033	19546	3%	0	63224	65084	3%	0
[J5-J4]	22203	22767	3%	0	20324	20958	3%	1	21875	22335	2%	0	71513	73464	3%	0

a) M42 Junction 5 southbound

Link	AM-Peak (veh/5 hrs)				Inter-Peak (veh/5 hrs)				PM-Peak (veh/5 hrs)				24 hours (veh)			
	[06:00-11:00]				[11:00-16:00]				[16:00-21:00]							
	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test
[J9-J10]	23616	24832	5%	1	25788	26982	5%	1	23469	24955	6%	1	83488	87708	5%	1
Junction 10	17962	18652	4%	1	19975	20633	3%	1	18343	18620	2%	0	64968	66475	2%	0
[J10-J10A]	20650	21681	5%	1	23099	23892	3%	1	22250	22513	1%	0	75731	77801	3%	0

b) M6 Junction 10 northbound

Link	AM-Peak (veh/5 hrs)				Inter-Peak (veh/5 hrs)				PM-Peak (veh/5 hrs)				24 hours (veh)			
	[06:00-11:00]				[11:00-16:00]				[16:00-21:00]							
	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test	Before	After	% diff	t-test
[J10A-J10]	19869	21421	8%	1	21166	22093	4%	1	18104	19297	7%	1	69508	72891	5%	1
Junction 10	17085	18029	6%	1	18165	19096	5%	1	15658	16731	7%	1	60198	62895	4%	1
[J10-J9]	23727	24649	4%	1	24158	25168	4%	1	21054	22313	6%	1	81037	84104	4%	1

c) M6 Junction 10 southbound

The data presented in Table 11 show that the 24 hour traffic flows on the M42 TJR section have increased by approximately 3.5% across all day-types for all sites considered within this study. This change is not in line with Department for Transport (DfT) statistics where the national motorway traffic level was recorded to have decreased by 2% during the first two quarters of 2010 compared to the same period in 2009 (DfT, 2010).

On the contrary, 24 hour traffic flows at the M6 TJR site were higher on all links and for all day-types in the after case when compared to the before case. A statistically significant increase in traffic flow was observed on all links except on the northbound carriageway within J10 and the [J10-J10A] link for the [Mondays] and [TWT] day-types. This change was on average, 4% and 5% in the northbound and southbound direction respectively between the before and after cases and did not reflect the DfT statistics that indicate national motorway traffic levels decreased by 1.6% in the period between the before and after cases (Mott MacDonald, 2008).

6.3.2. 15 minute maximum flows

The 15 minute maximum flow measures the maximum number of vehicles observed passing a particular point on the motorway over a 15 minute period.

To overcome the disadvantage of averaging data over the whole study period, or using the absolute maximum value, the 80th percentile of the cumulative frequency for the 15 minute maximum flow observed was used as a measure to estimate the change in capacity between the before and after cases. This approach was adopted from the ATM 12 month report, where it was assumed that the top 20% of the observed 15 minute maximum flows represent cases of unsustainable flow or unusually high throughput, due to a temporal change in traffic conditions (Sultan et al, 2008; Ogawa et al, 2009, 2010, 2011).

Table 12 shows the 80th percentile of the cumulative frequency for the 15 minute maximum flow, observed over 24 hours.

Table 12: 80th percentile of the cumulative frequency for the 15 minute maximum flow

	Upstream [J6-J5]	Within J5	Downstream [J5-J4]
Before	6763	5977	6837
TJR	6760	6068	6912
% diff	0%	2%	1%
t-test	0	0	0

a) M42 Junction 5

	Northbound			Southbound		
	Upstream	Within J10	Downstream	Upstream	Within J10	Downstream
	[J9-J10]	[J10-J10A]		[J10A-J10]	[J10-J9]	
Before	6273	4968	6185	5553	4750	5888
After	6845	5277	6484	5791	4972	6282
% diff	9%	6%	5%	4%	5%	7%
t-test	1	1	1	1	1	1

b) M6 Junction 10

M42 Junction 5

The cumulative percentage and frequency histograms for the observed 15 minute maximum flows were produced for both the before and TJR cases. Data for the M42 section has been normalised due to the difference in “days in period” between the before and after cases, as identified earlier in Section 5.2 There are no noteworthy changes in the shapes of the histograms between the two cases.

The data presented in Table 12 shows that on average, across all three M42 TJR sites, there was a 1-2% increase in the observed maximum throughput during TJR when compared to the before (i.e. no-TJR) case. However, note that this change was not statistically significant.

M6 Junction 10

At M6 Junction 10, all links considered links showed a statistically significant increase in the 80th percentile flow, with an average 7% increase observed along the section. In addition, it should be noted that in the before case, the 80th percentile flow on all links was on average 2000 veh/hr/lane (and up to 2100 veh/hr/lane), exceeding the 1963 veh/hr/lane (or 5888 veh/hr across all three lanes) theoretical design capacity for a typical motorway in the UK (Ogawa et al, 2009). This gives a strong indication that this section of road suffered from high traffic demand during the before case. However, it should be noted that that this observation is likely to be attributed to the

introduction of HSR operations on this section of road, as smart motorways was not in operation at this site prior to the introduction of TJR.

During the after case, the 80th percentile flows were on average 1600 veh/hr/lane (and up to 1700 veh/hr/lane), which is lower than the theoretical capacity of 1963 vehicles/hour/lane (or 7850 vehicles/hour across four lanes). If only three lanes were in operation during the after case, this section would not have been able to accommodate the traffic levels observed in the after case for sustained periods of time. This indicates that the use of the hard shoulder as an additional running lane has provided a clear benefit in terms of the volume of extra traffic that could flow through the scheme during the after case.

6.4. Lane Utilisation

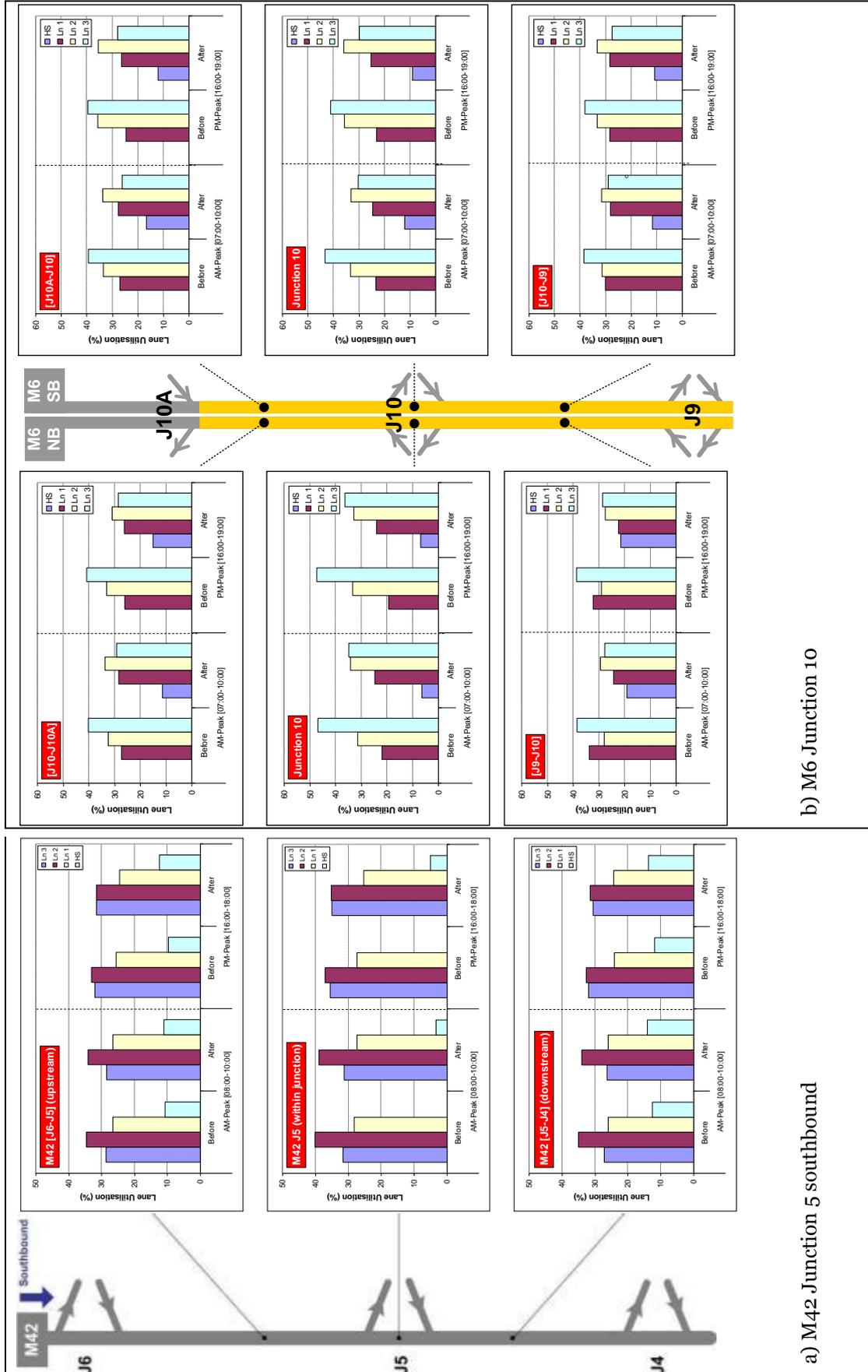
Lane utilisation was studied to understand the impact of TJR on hard shoulder utilisation and distribution of traffic between lanes was evaluated over the following periods:

Table 13: Lane utilisation evaluation periods

	M42 Junction 5	M6 Junction 10
AM-Peak	08:00 – 10:00	07:00 – 10:00
PM-Peak	16:00 – 18:00	16:00 – 19:00

These time intervals were chosen as they represent periods in which HSR is typically in operation across all day-types. In general, HSR was in operation for a longer duration on the M6 section when compared to the M42 and other M6 smart motorway sections. It is considered that this is due to the higher level of average traffic flows observed throughout the peak periods.

Figure 34: Lane Utilisation, [TWT]



M42 Junction 5

Overall, the data has shown an increase in hard shoulder utilisation across all day-types during the AM-Peak and PM-Peak periods. The findings for the M42 TJR site can be summarised as follows:

- Average hard shoulder utilisation increased from 10% to 11.5% on the link upstream of the junction across all day-types
- Average hard shoulder utilisation increased from 12% to 14% on the link downstream of the junction across all day-types
- Average hard shoulder utilisation through the junction was 4.5% across all day-types

M6 Junction 10

The findings for the M6 TJR site can be summarised as follows:

- On the northbound [J9-J10] link, average hard shoulder utilisation was approximately 20% across all day-types. Lane utilisation (i.e. distribution of traffic across the carriageway) was also observed to be evenly spread on this link, which may be due to the fact that approximately 24% of the traffic leaves the M6 at J10.
- Average hard shoulder utilisation at J10 northbound, where TJR is in operation, was 7.0% across all day-types; i.e. higher than the results found at the M42 part-time TJR site
- On average across all day-types, hard shoulder utilisation on the [J10A-J10] and [J10-J9] links was 12.5%. This figure is comparable to the M42-MM and BBMM Phase 1 sites.
- Average hard shoulder utilisation at J10 southbound, where TJR is in operation, was 10.5% across all day-types. Similar to the northbound direction, this figure is higher than the results found at the M42 part-time TJR site.

Summary of key findings

Overall, low usage of the hard shoulder was observed at both part-time (M42) and full-time (M6) TJR sites. Although higher utilisation was observed at M6 J10, the figures are still relatively low when compared to the hard shoulder utilisation between junctions. The observations made within this section indicate that motorists:

- may not be aware of TJR
- may not want to use the hard shoulder through the junction
- may want to use the hard shoulder through the junction but are not sure whether they can.

Although a small increase in hard shoulder utilisation was observed both upstream and downstream of the junction, it is difficult to identify the reason for this change. It is possible that the increase is due to TJR, however, it may also be due to a number of factors which are discussed later within Sections 6.6 (driver behaviour), 6.7 (percentage of heavy goods vehicles) and 6.5 (speed differential between lanes) of this report.

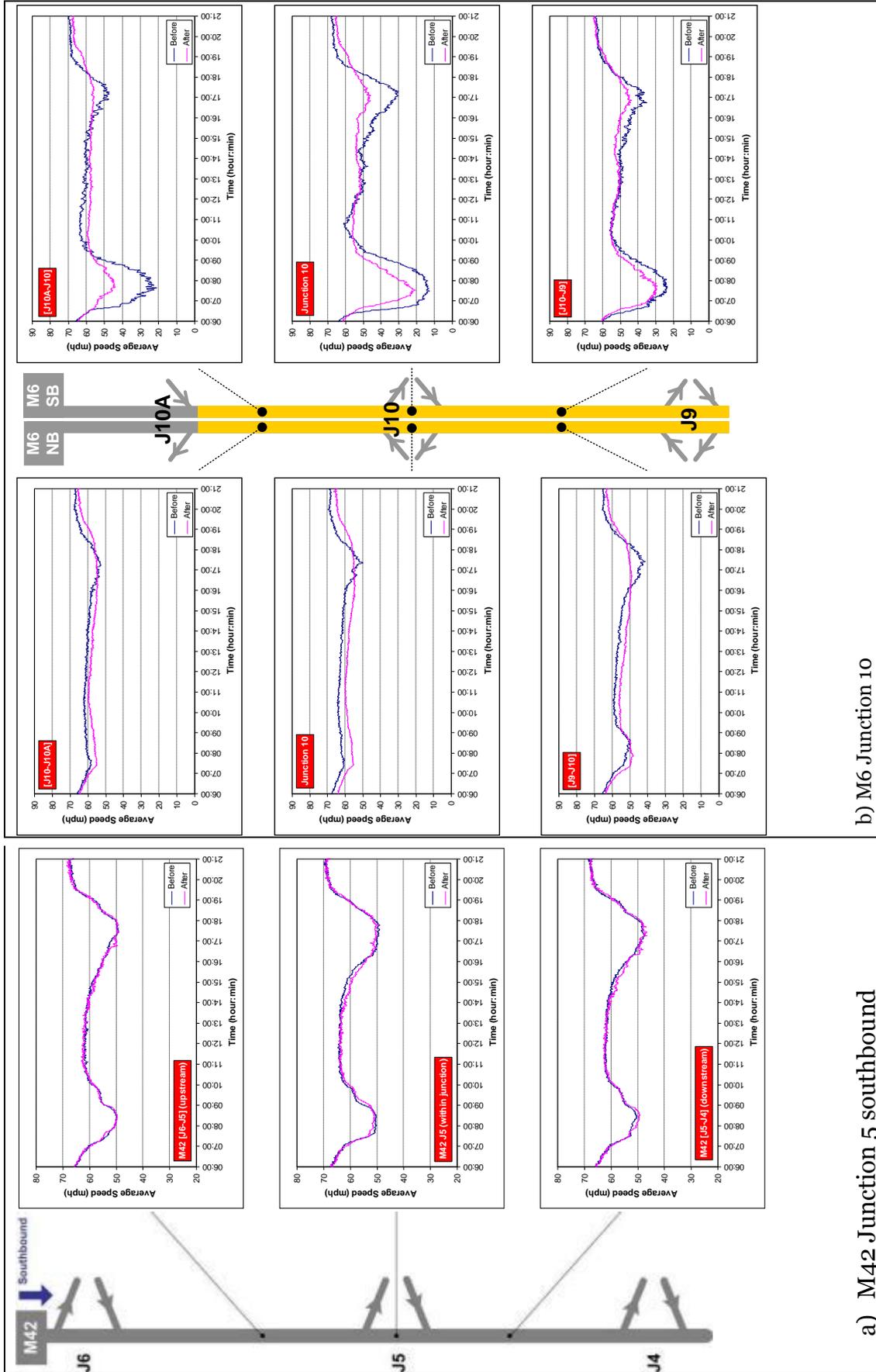
6.5. Speed analysis

6.5.1. Average Speed Profiles

Figure 35 shows the average speed profiles for [TWT] across all lanes. For the M42 section, the data shows that the average speed profiles of the before and after cases are generally similar, although there were some deviations between the two cases. Average speeds appeared to be lower during some of the AM-Peak and PM-Peak periods, which is likely to be associated with the increase in traffic flows shown in Section 6.3, and different speed signal settings being implemented at different times. The average speed of vehicles within the junction is higher by approximately 2 mph than on the upstream and downstream links for all day-types in both before and after cases. This is particularly noticeable during the Inter-Peak periods, when VMSL is not commonly in operation.

On the contrary, average speeds in the northbound direction during the AM-Peak and Inter-Peak periods were lower in the after case than those in the before case for the M6 section. This result was expected and is largely attributed to the introduction of VMSL used during HSR operations, which restrict vehicle speeds to a maximum of 60 mph during periods of congestion. In southbound direction, all links on BBMM2 southbound direction suffered from severe traffic congestion, with average speeds dropping below 40 mph (and on some links below 30 mph) during some periods during the before case. A noticeable increase in average speed and smoother changes in speed profiles occur in the after case during parts of the AM-Peak and PM-Peak periods.

Figure 35: Average speed profiles [TWT]



6.5.2. *Speed differential between lanes*

One of the aims of Smart motorways is to smooth traffic flow by setting Variable Mandatory Speed Limits during periods of congestion. An indication of whether this has been achieved is by assessing the difference in average speed between lanes.

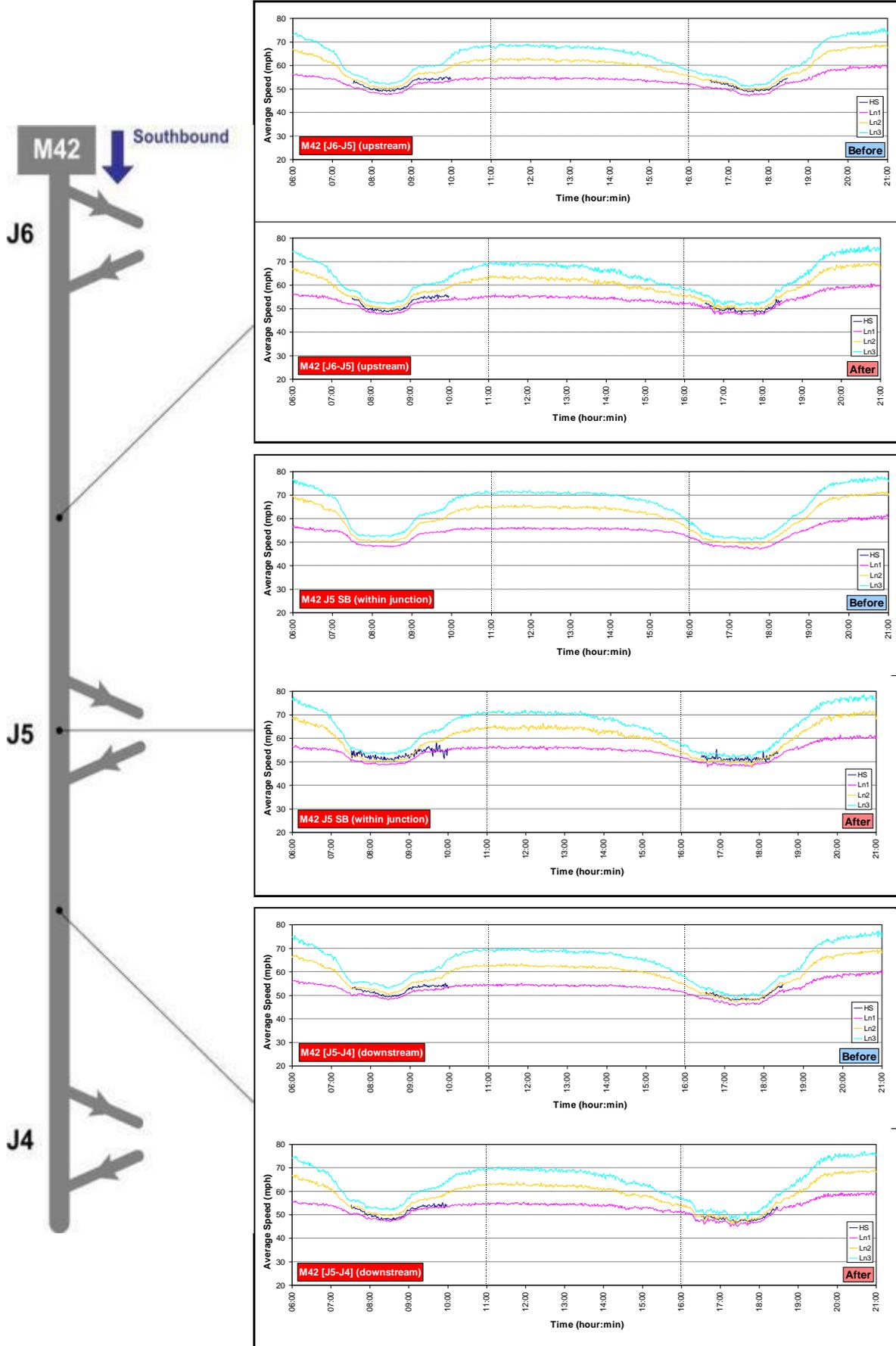
Figure 36 shows the speed differential between lanes for the [TWT] day-type; the data for [Mondays] and [Fridays] is presented in Appendix I and results are similar.

The results show that:

- The average speed profiles at the upstream, downstream and within the junctions after the introduction of TJR are similar to before TJR. This indicates that TJR has not led to any deterioration in the average speed of traffic travelling along this section of road.
- The average speed profiles on the hard shoulder upstream and downstream of the junction are comparable to other lanes for both before and after cases. The average speed on the hard shoulder is almost always marginally higher than lane 1. This result is consistent with the findings from the HSR60 report (Ogawa et al, 2009).

The average speed on the hard shoulder within the junction was observed to be almost always higher than the average speed on both lane 1 and lane 2. This observation is supported by the findings presented in Section 6.4 where the analysis indicated that HGVs, which on average travel slower than other vehicles, generally travel along the main carriageway instead of the hard shoulder through the junction. This may indicate that some of the hard shoulder traffic is undertaking slower moving traffic in lane 1. This type of behaviour was observed during the video analysis, although this analysis only measured lane changing movements. Without further video evidence this cannot be proven. Also, as the level of traffic on the hard shoulder is less than that of lane 1 those reluctant to undertake, or who are obeying the Highway Code, may be moving into the outer lanes to overtake slower moving traffic in lane 1 (likely to be HGVs). This implies that HGVs may be preventing a greater level of hard shoulder use through the junction.

Figure 36: Speed differential between lanes, [TWT]



6.6. Driver Behaviour

6.6.1. Methodology

CCTV footage was analysed to identify specific lane changing movements of traffic at the merge and diverge of the junction. The duration of the footage analysed is found Table 14 and the days studied are found within the appendices (xxx). The analysis focused on the categories of behaviour identified at both the merge and diverge of the junction.

Table 14: CCTV footage analysis hours

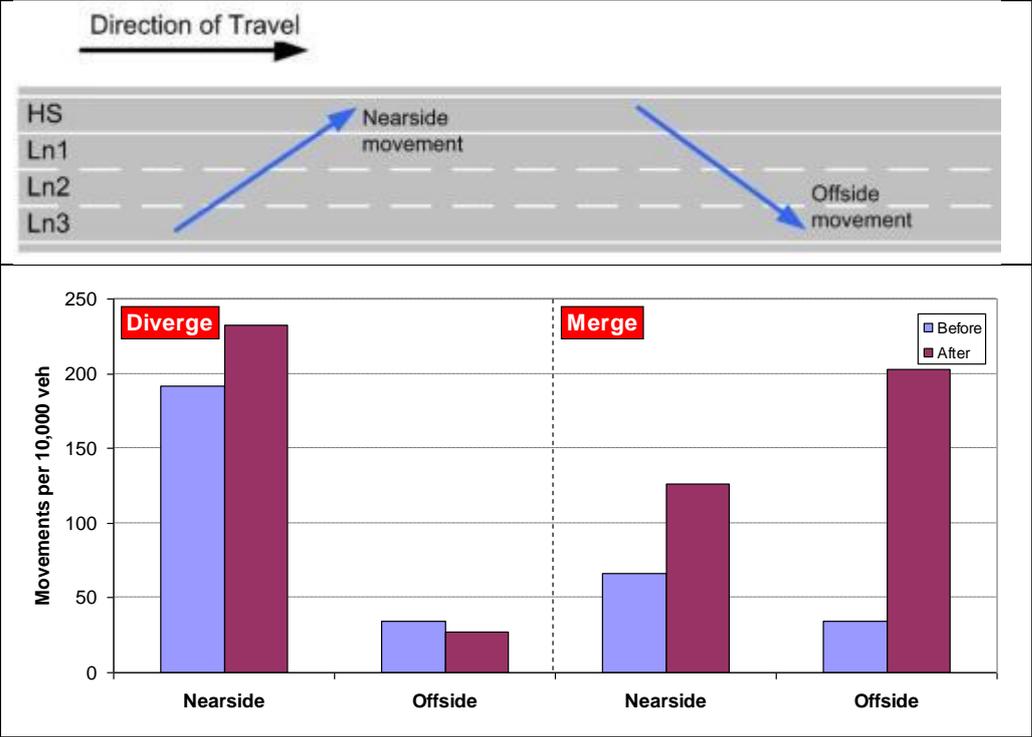
	M42 Junction 5	M6 Junction 10
Before	60 hrs	101.5 hrs
After	60 hrs	40 hrs

It should be noted that there was a slight difference in the camera view between the before and after case due to the position and angle of CCTV cameras. Also, due to the manual nature of the data extraction, the analysis has a certain level of subjectivity associated with it. Consistency between analysts has been maintained by cross-checking the logs. The objective of the driver behaviour study is to understand how the road space is utilised during smart motorways at a junction, how lane behaviour affects the performance of smart motorways, and to identify any key issues which affect the overall efficiency and safety of the system.

6.6.2. Summary of Results – M42 Junction 5

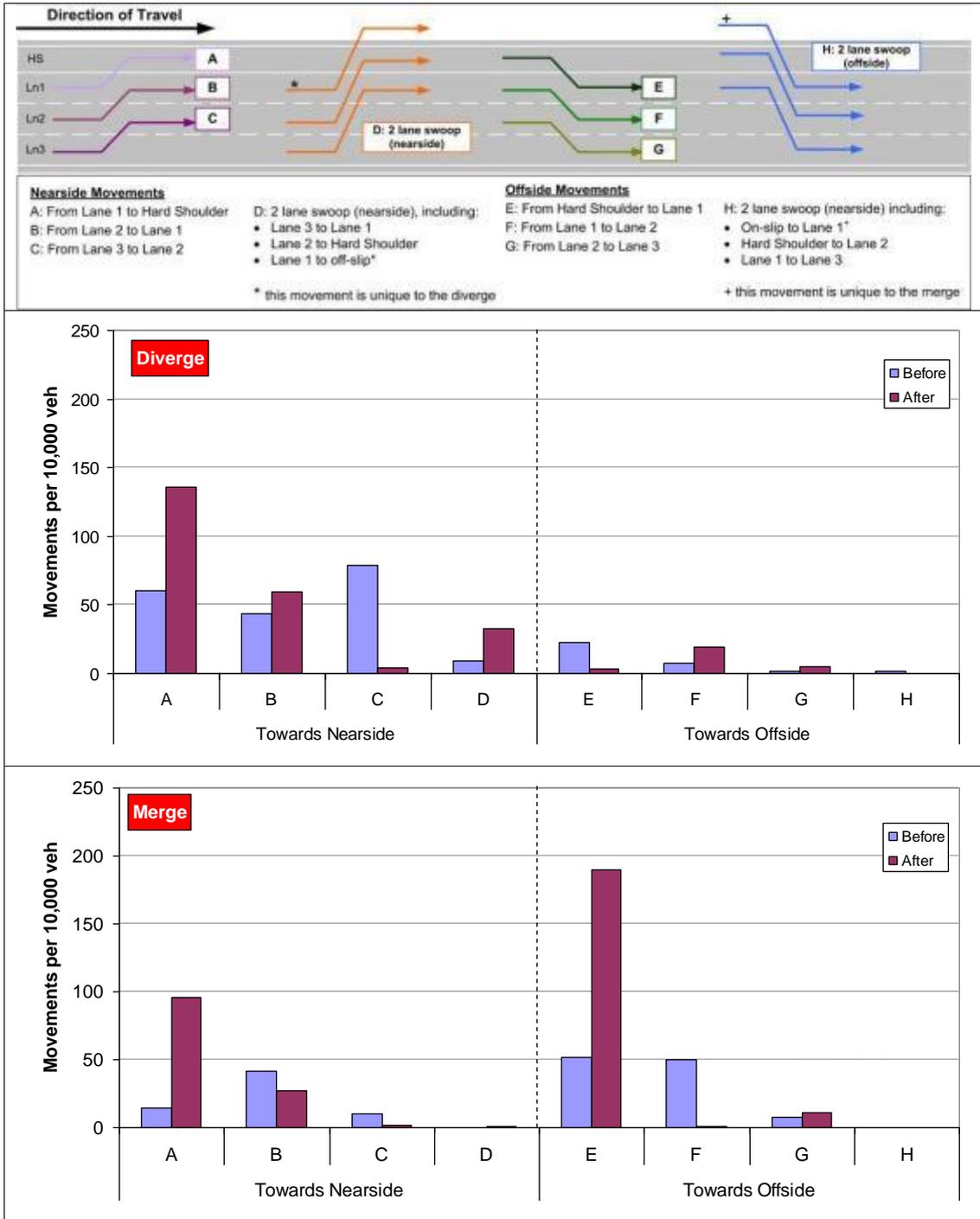
The total number of vehicle movements per 10,000 vehicles at the Junction 5 southbound diverge and merge are presented in Figure 37. The figure shows that there was a noticeable increase in vehicle movements at both locations, except for offside movements at the junction diverge.

Figure 37: Total vehicle movements (per 10,000 vehicles) at M42 Junction 5 diverge and merge



To provide a better understanding of the observations made in Figure 37, driver behaviour was studied in further detail. Figure 38 compares the observed vehicle movements at J5 southbound for the before and after cases.

Figure 38: Driver movements at M42 J5 Southbound



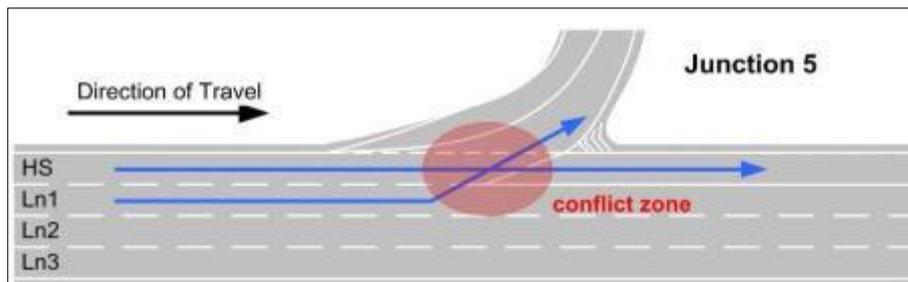
The analysis of video data has shown the following:

At the diverge

A reduction in the number of offside lane changes from the hard shoulder to lane 1 (movement E) was observed, indicating a potential benefit of TJR as motorists are able to continue along the hard shoulder at the junction without having to change lane back to the main carriageway.

Contrary to the above, an increase in the number of nearside lane changes from lane 1 to the hard shoulder (movement A) was also observed. This is largely due to vehicles on lane 1 joining the hard shoulder after the diverge, which may indicate that some road users are reluctant to cross the solid white line across the hard shoulder at this location. However, movement A also includes vehicles exiting the motorway junction at this location; i.e. performing a 2 lane swoop (nearside) from lane 1 to the J5 off-slip. An increase in this type of behaviour was observed which is a concern, especially during TJR operation as there is a conflict between traffic going through the junction on the hard shoulder and traffic exiting at J5 from Lane 1 as illustrated in Figure 39.

Figure 39: Conflict at M42 Junction 5 Diverge



At the merge

An increase in the number of nearside lane changes from lane 1 to the hard shoulder (movement A) was observed. This movement took place mostly after the merging point and may indicate that motorists are using the hard shoulder in a similar manner to the before case.

An increase in the number of offside lane changes from the hard shoulder to lane 1 (movement E) was observed. Although this movement includes traffic giving-way to merging traffic prior to the merging point, it took place mostly after the merge by vehicles joining the hard shoulder, which subsequently moved to lane 1. This was not categorised as a 2 lane swoop (offside) from the J5 on-slip to lane 1 as the lane change was not undertaken in one manoeuvre.

Overall, the video analysis supports the findings described in Section 6.4, where a small increase in hard shoulder utilisation was observed. However, the findings from this analysis has highlighted the possible lack of understanding of TJR operations, with a particular concern of vehicles continuing to leave Junction 5 at the diverge.

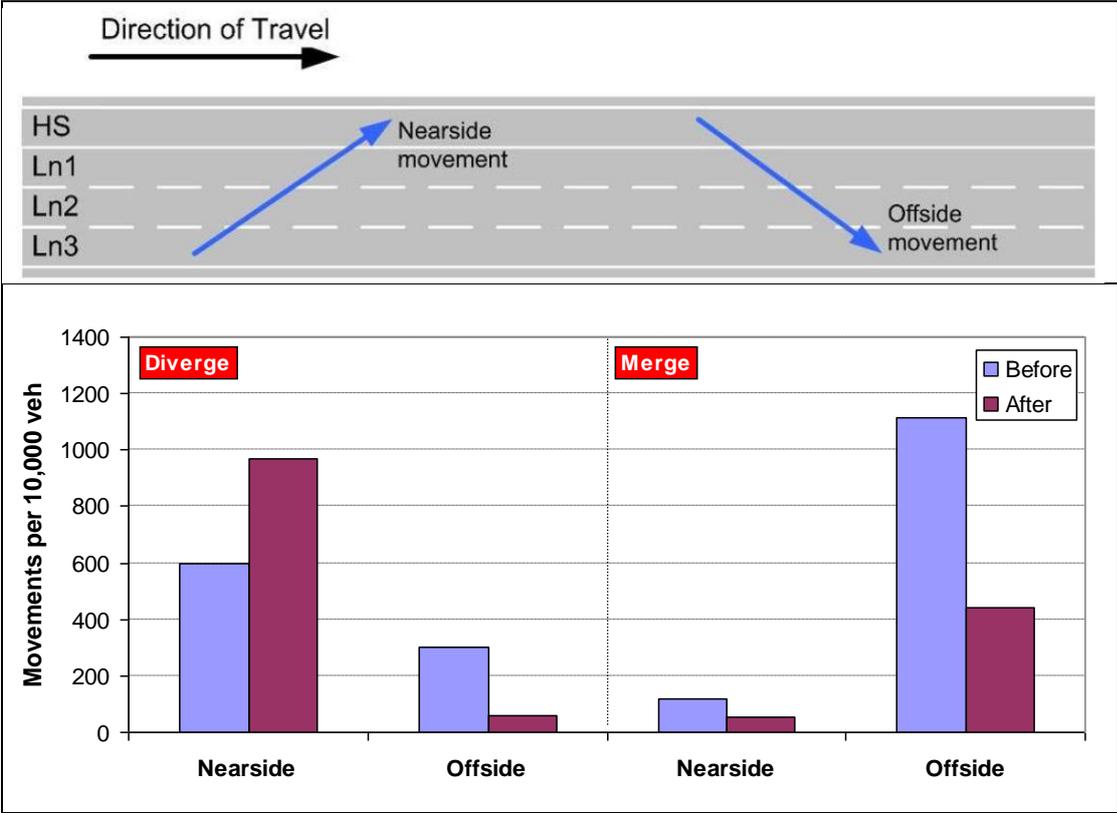
6.6.3. Summary of Results – M6 Junction 10

The total number of vehicle movements per 10,000 vehicles at J10, northbound and southbound, merge and diverge is presented in Figure 40. The figure shows that at J10 diverge, there was an increase in nearside movements, and a decrease in offside movements following the introduction of TJR. There were also more nearside movements than offside movements at this location in both before and after cases.

At the J10 merge, there was a decrease in both nearside and offside movements following the introduction of TJR. There were also more offside movements than nearside movements at this location in both before and after cases. These findings are consistent with the findings from the M42 J5 TJR site.

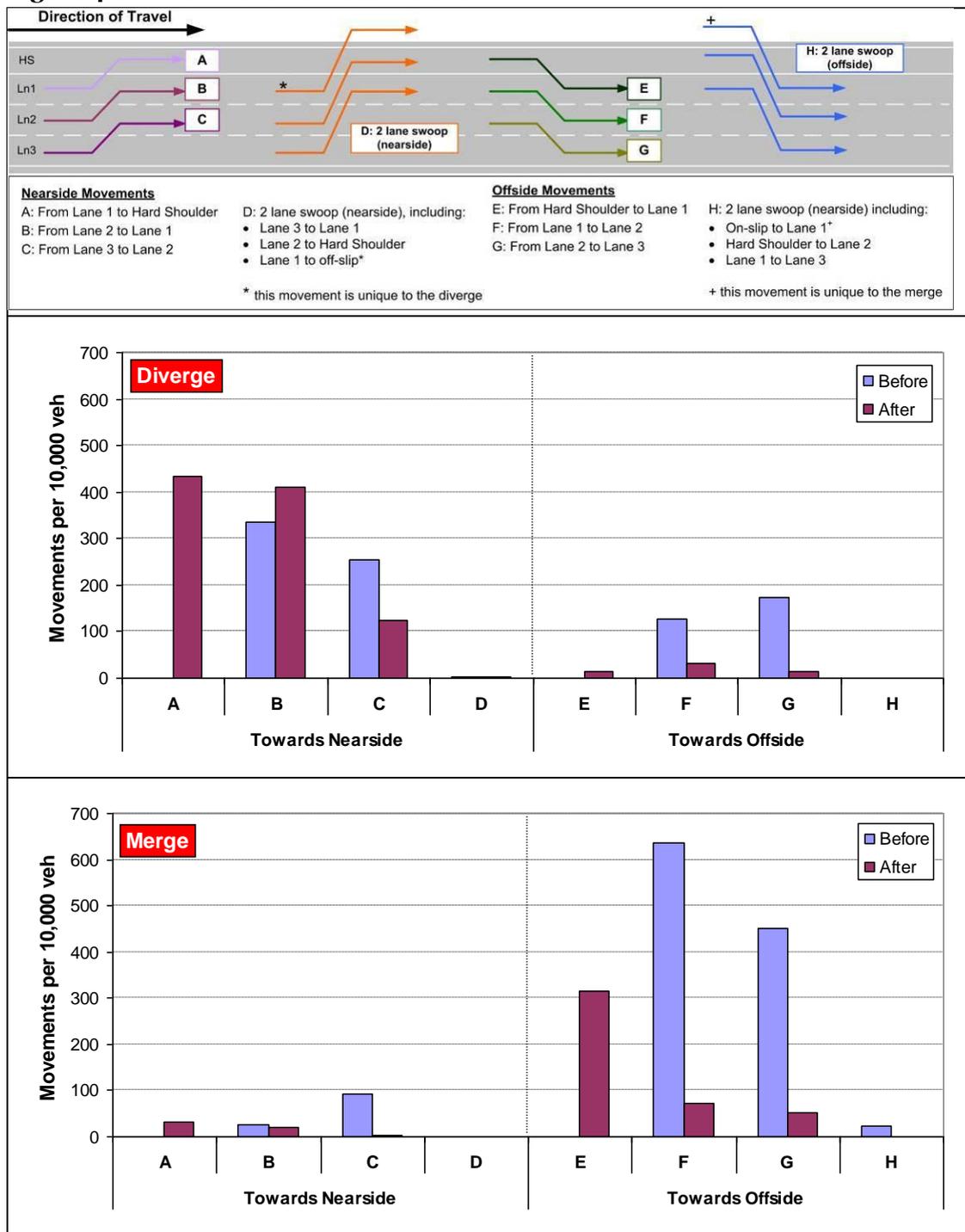
The data shows that in the after case, there were less movements with approximately 2100 vehicle movements per 10,000 vehicles and 1500 vehicle movements per 10,000 vehicles in the before and after cases respectively.

Figure 40: Total vehicle movements (per 10,000 vehicles) at M6 J10 diverge and merge



To provide a better understanding of the observations made in Figure 40, driver behaviour was studied in further detail. Figure 41 compares the observed vehicle movements at J10 for the before and after cases.

Figure 41: Driver movements at M6 J10



Note: i) Movements A and E were not applicable in the before case.

Overall, the analysis of video data has shown more vehicle movements per 10,000 vehicles when compared to the M42 TJR site. The total number of vehicle movements per 10,000 vehicles at M42 J5 southbound was observed to be less than 250 vehicles at both the merge and diverge. This observation is associated with the higher level of traffic flows observed on the M6 throughout the peak periods as reported in Section 6.3. The following observations can also be made:

At the diverge

- In the after case, an increase in the number of nearside lane changes from lane 2 to lane 1 (movement B) was observed. This is likely to be a result of vehicles on lane 1 joining the hard shoulder after the junction diverge (i.e. movement A).
- A reduction in the number of offside lane changes (movement F – lane 1 to lane 2, and movement G – lane 2 to lane 3) was observed. This is a result of the increase in nearside movements observed.
- 2 lane swoop movements, where vehicles leaving the motorway at this location from lane 1 to the off-slip, were not observed in the after case. This is a positive result as this demonstrates that the potential conflict in driver movement between traffic going through the junction on the hard shoulder and traffic leaving the TJR site, i.e. from lane 1 to the slip road, was not observed during the study period.

At the merge

- The overall reduction in vehicle movements at the merge between the before and after cases indicates that more traffic is able to continue on the motorway without changing lanes at this location. This indicates a reduction in vehicle conflict.

- In both the before and after cases, more offside movements were observed than nearside movements. In the after case, a high proportion of offside lane changes from the hard shoulder to lane 1 (movement E) was observed, indicating that traffic was giving-way to traffic merging at J10. This also resulted in a reduction in offside lane changes (movement F – lane 1 to lane 2, and movement G – lane 2 to lane 3). This observation is similar to findings from the M42 TJR study.
- A nearside lane change from lane 1 to the hard shoulder (movement A) was only possible following the implementation of TJR. This movement took place mostly downstream of the merging point.
- In the after case, a decrease in the number of nearside lane changes from lane 2 to lane 1 (movement B) and lane 3 to lane 2 (movements C) was observed. This supports the findings above, that traffic was giving-way to traffic merging at J10.

Summary of key findings

One of the key differences in traffic behaviour between the M42 TJR and M6 TJR sites was observed at the junction diverge. At the M42 TJR site diverge, vehicles on lane 1 were observed to join the hard shoulder after the diverge, indicating that some road users were reluctant to cross the solid white line across the hard shoulder at this location. In addition, many 2 lane swoops (nearside) from lane 1 to the off-slip was also observed at the M42 TJR site, which was a safety concern especially during TJR operation as there is a conflict between traffic going through the junction on the hard shoulder and traffic exiting at J5 from Lane 1. Traffic flows are higher at the M6 TJR site than the M42 TJR site so the difference in road markings used in the part-time and full-time TJR operations contributed to the different traffic behaviours observed. At the M42 TJR site, where part-time TJR is in operation, a solid white line crossing the hard shoulder is present which may cause some road users to be reluctant to cross it. This road marking is not present at the M6 J10 site, and has contributed to safer road conditions by reducing confusion at this location.

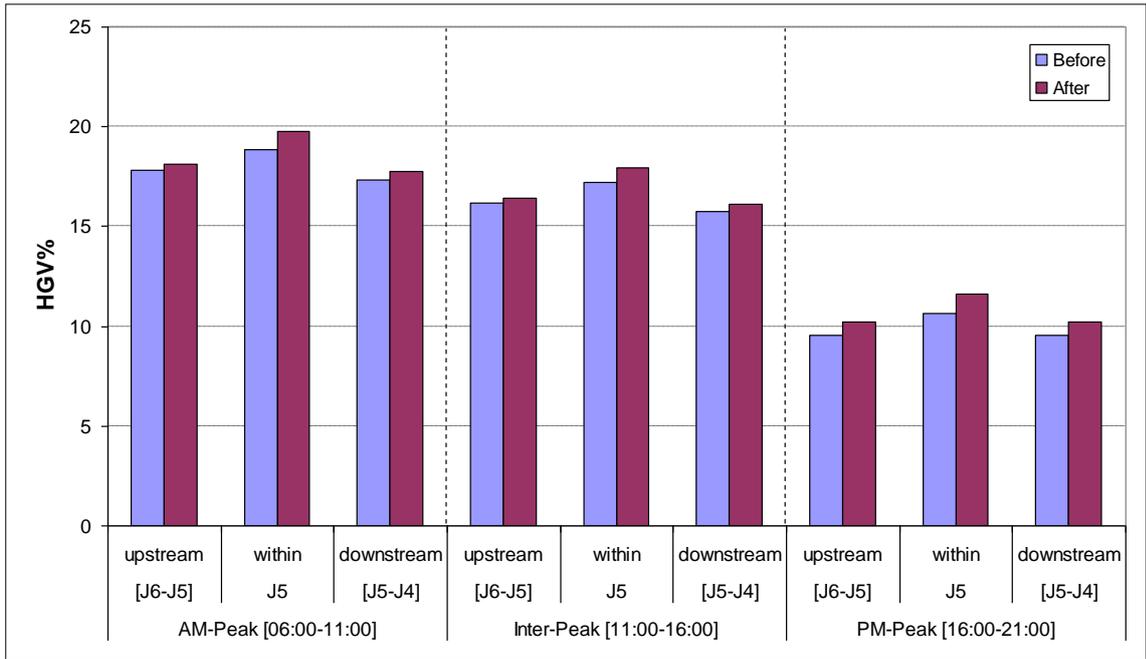
6.7. Traffic composition

6.7.1. Percentage of Heavy Goods Vehicles

The percentage of Heavy Good Vehicles (HGV%) helps to understand the composition of traffic on a motorway section. MIDAS loop data classifies vehicles into four categories according to their lengths, and within this study, as in all previous Smart motorways monitoring and evaluation reports, category 3 and category 4 vehicles (vehicles 6.6 m or longer), have been considered as an HGV.

Figure 42 presents the average HGV% on the M42 TJR section for the [TWT] day-type and each peak period.

Figure 42: Percentage of Heavy Goods Vehicles [TWT]



By combining the HGV% results with the traffic flow levels presented in Section 6.3, the data has shown the following:

- There is a higher proportion of HGV traffic within the TJR section during the AM-Peak and Inter-Peak periods than the PM-Peak periods across all day-types. This shows that there is less HGV traffic travelling within the TJR section during the PM-Peak period.

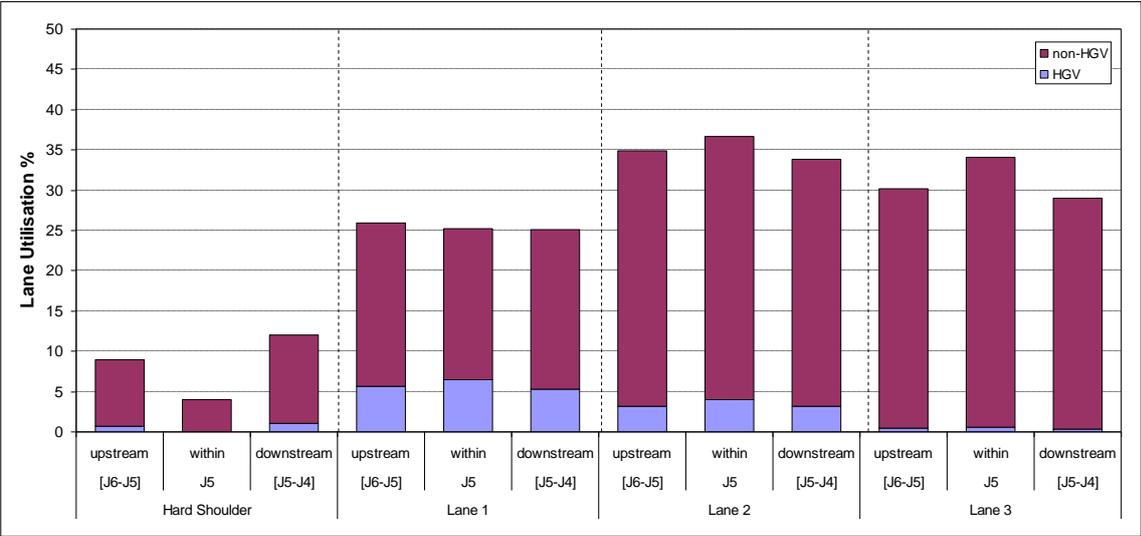
- The upstream and downstream links showed similar HGV% for all day-types, when compared to the before case.
- There is an average increase in HGV% of 0.5% and 1.0% in the links and within the junction respectively.
- A high proportion of HGV traffic continues on the motorway at this junction.

6.7.2. *Percentage of Heavy Goods Vehicles per lane*

To understand the observations made in relation to lane utilisation (Section 6.4) and lane changing behaviour (section 6.6), traffic composition within Junction 5 was studied on a lane-by-lane basis. The study was undertaken for July 2010 using IVD, covering periods where 50 mph and 60 mph speed restrictions were in place (i.e. HSR was in operation).

Figure 43 shows that during July 2010, the hard shoulder within Junction 5 was used only by a very small number of HGVs. This suggests that HGVs are reluctant to use the hard shoulder through the junction, which in turn may lead to some other motorists being reluctant to use the hard shoulder to avoid undertaking on the nearside lanes (as discussed in Section 6.5 where speeds on the hard shoulder were observed to be greater than speeds on lane 1). Strategic HGV traffic travelling from the north to the south is likely to have joined the TJR section in lane 1 and may therefore be reluctant to move into the hard shoulder for the whole length of the M42-MM section. However, this observation has been made at one site over a one month period, where IVD data was only collected for 15 days due to technical issues associated with data download. Hence it is recommended that further analysis is undertaken to understand this observation.

Figure 43: Distribution of HGV traffic across lanes, M42 J5 Southbound, July 2010

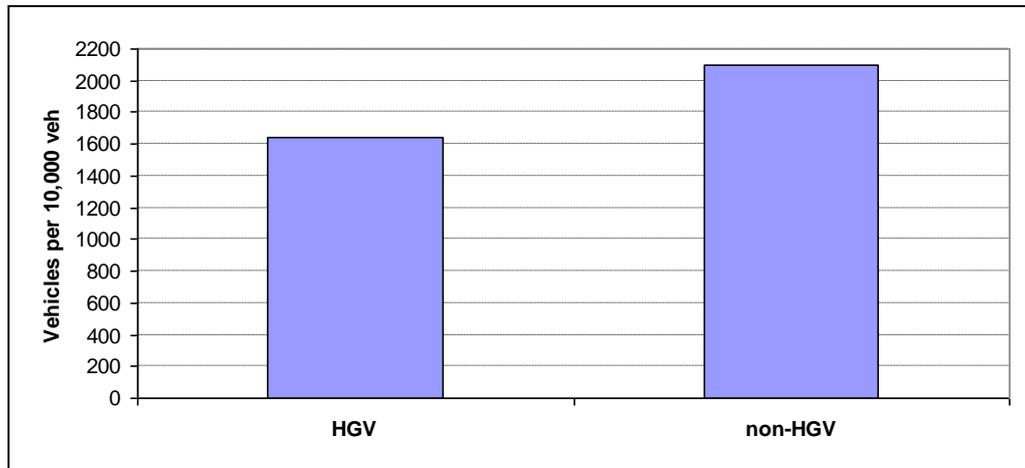


Through the junction

Within the M42 J5 TJR study, traffic composition was studied on a lane-by-lane basis to understand the observations made in relation to lane utilisation using IVD. The analysis identified that the hard shoulder within Junction 5 was used by only a very small number of HGVs, suggesting that HGVs were reluctant to use the hard shoulder through the junction, which in turn may lead to some other motorists being reluctant to use the hard shoulder to avoid undertaking on the nearside lanes.

As IVD was not available for the M6 Junction 10 study, vehicle types travelling on the M6 through J10 was recorded as a part of the video analysis. The results are summarised in Figure 44.

Figure 44: Vehicles per 10,000 vehicles using the hard shoulder through M6 J10 northbound



The results show that, of the total vehicles using the hard shoulder through the junction at J10 northbound, 44% were HGVs. This is a positive result as few HGVs were observed on the hard shoulder at the M42 J5 site, although it should be noted that this may have been due to the spare capacity available at this site. In addition, strategic HGV traffic travelling from the south to the north is more likely to use the hard shoulder through the junction as [J10-J10A] (downstream) link is long, and they do not need to move back into lane 1 until J10A.

6.8. Other indicators

This sub-section provides the findings from the analysis of other traffic indicators for the M42 TJR section only. Analysis was not carried out for the M6 TJR section as the before case represents a non-smart motorway case (i.e. normal road conditions), therefore the results would not represent the impact of TJR operations on traffic conditions in isolation.

6.8.1. Journey time analysis

Average journey times

Table 15 shows the average journey time for each 5 hour peak period between [J6-J5] mid-link to [J5-J4] mid-link in the southbound direction. The cells in green represent where there was a reduction in the average journey times between the before and after cases. The data shows that, on average, there was little change in journey times for any of the day-types during the peak periods. This result is to be expected as both cases operated under HSR60 and that no significant changes in traffic demand were observed.

Table 15: Average Journey Times, [J6-J5] mid-link to [J5-J4] mid-link (before vs. after)

ORs	AM-Peak (06:00-11:00)			Inter-Peak (11:00 - 16:00)			PM-Peak (16:00 - 21:00)		
	Mon	TWT	Fri	Mon	TWT	Fri	Mon	TWT	Fri
Before (min:sec)	03:41	03:36	03:26	03:20	03:22	03:44	03:30	03:38	03:45
After (min:sec)	03:44	03:36	03:28	03:21	03:24	03:46	03:30	03:38	03:43
Difference (min:sec)	00:03	00:00	00:02	00:01	00:02	00:02	00:00	00:00	-00:02
% change	1.4%	0.0%	1.0%	0.5%	1.0%	0.9%	0.0%	0.0%	-0.9%

The journey time profiles for each day-type have been examined to gain a better understanding of the results found above over time. Figure 45 shows the average journey time profiles between [J6-J5] mid-link to [J5-J4] mid-link in the southbound direction for [TWT].

Figure 45: Average Journey Time, [J6-J5] mid-link to [J5-J4] mid-link [TWT]

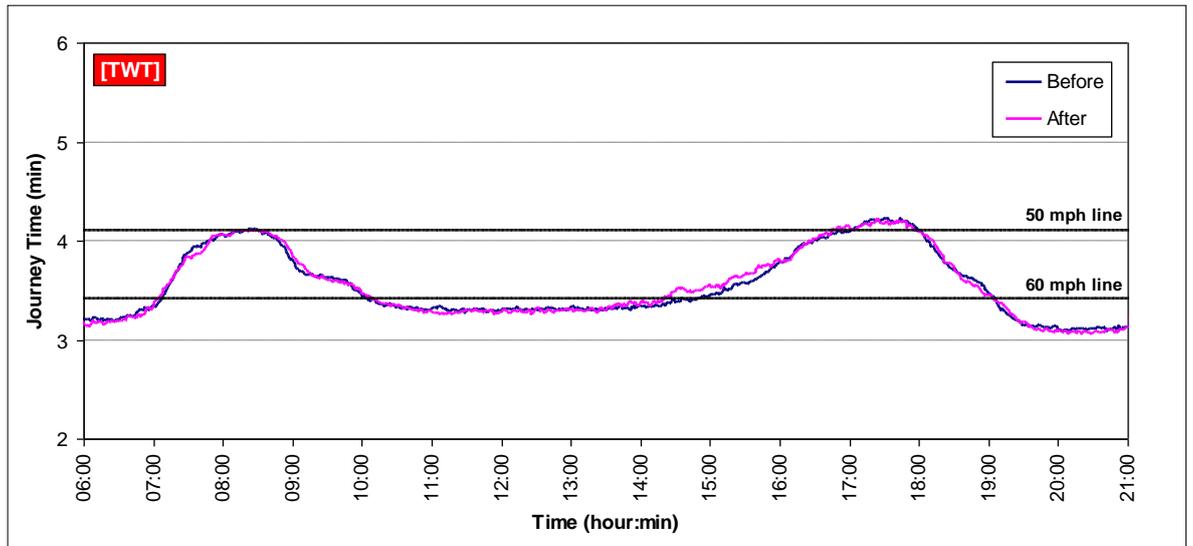


Table 15 and Figure 45 show that the average journey times are generally similar between the before and after cases. An increase in average journey times shown at the latter end of the Inter-Peak is likely to be due to an increase in traffic demand during this period.

Variability in Journey Times

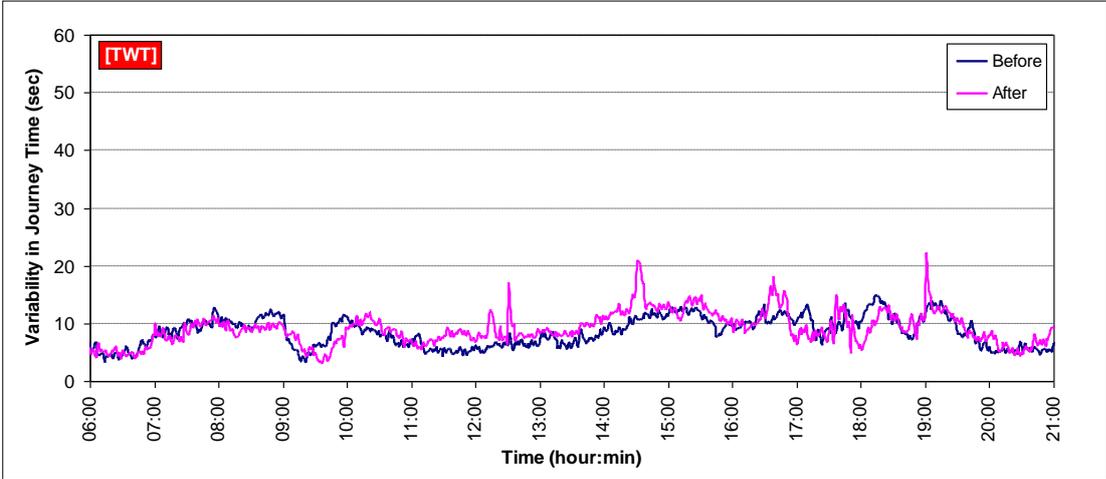
Table 16 shows the variability (standard deviation) in average journey times for each 5 hour peak period between [J6-J5] mid-link and [J5-J4] mid-link in the southbound direction. The cells highlighted in green represent a reduction (benefit) in variability between the two cases.

Table 16: Variability of Average Journey Times, [J6-J5] mid-link to [J5-J4] mid-link

ORs	AM-Peak (06:00-11:00)			Inter-Peak (11:00 - 16:00)			PM-Peak (16:00 - 21:00)		
	Mon	TWT	Fri	Mon	TWT	Fri	Mon	TWT	Fri
Before (min:sec)	00:07	00:08	00:05	00:08	00:08	00:09	00:08	00:09	00:08
After (min:sec)	00:06	00:07	00:06	00:08	00:10	00:11	00:06	00:09	00:09
Difference (min:sec)	-00:03	-00:01	00:01	00:00	00:02	00:02	-00:02	00:00	00:01

The data shows little change in the variability in average journey times between the before and after cases for any of the day-types. The profiles of variability in average journey times for each day-type have been examined to give a better understanding of the results found above. Figure 46 shows the variability of journey times between 06:00 and 21:00 hrs for [TWT] and that there is little difference between the two cases. Similar to the findings in Section 6.5, this result is to be expected as both cases operated under HSR60 and that no significant changes in traffic demand were observed.

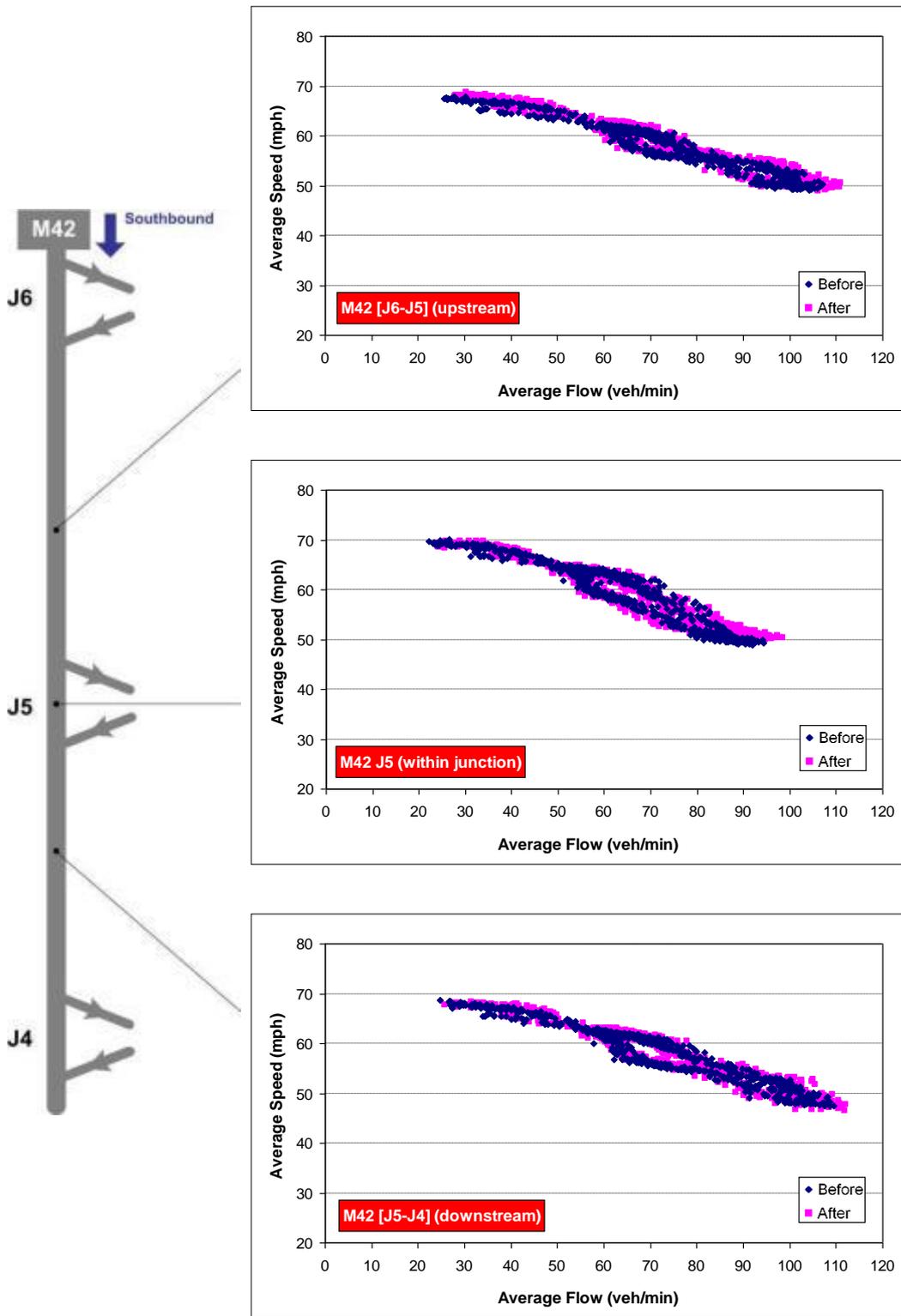
Figure 46: Variability in Journey Times, [J6-J5] mid-link to [J5-J4] mid-link [TWT]



6.8.2. *Average Speed/Flow Relationships*

Average speed/flow plots help to give an understanding of the level of congestion and capacity of a motorway section. Figure 47 presents the average speed/flow relationship on [TWT] for the before and after cases. Graphs for the other day-types are presented in Appendix G and show similar results.

Figure 47: Average Speed/Flow Relationships [TWT]



The results show that there is little difference in maximum throughput and average traffic speeds between the before and after cases. This supports the results found in Section 6.3 where no significant change in 15 minute maximum flow was found and in Section 6.5 where no change in average traffic speeds were observed between the before and after cases for all links within the assessed period.

In addition, the results showed no points corresponding to low flow and low speeds. This result coupled with the finding in Section 6.4 where the average hard shoulder utilisation within the junction was found to be on average only 4.5%, indicates that there is potentially some spare capacity available within the TJR section. However, this is likely to be due to the operation of HSR and TJR in combination, as flow breakdown was observed at the junction on a number of days when the downstream hard shoulder was not open.

6.8.3. *Speed Limit Compliance*

Main Carriageway Compliance

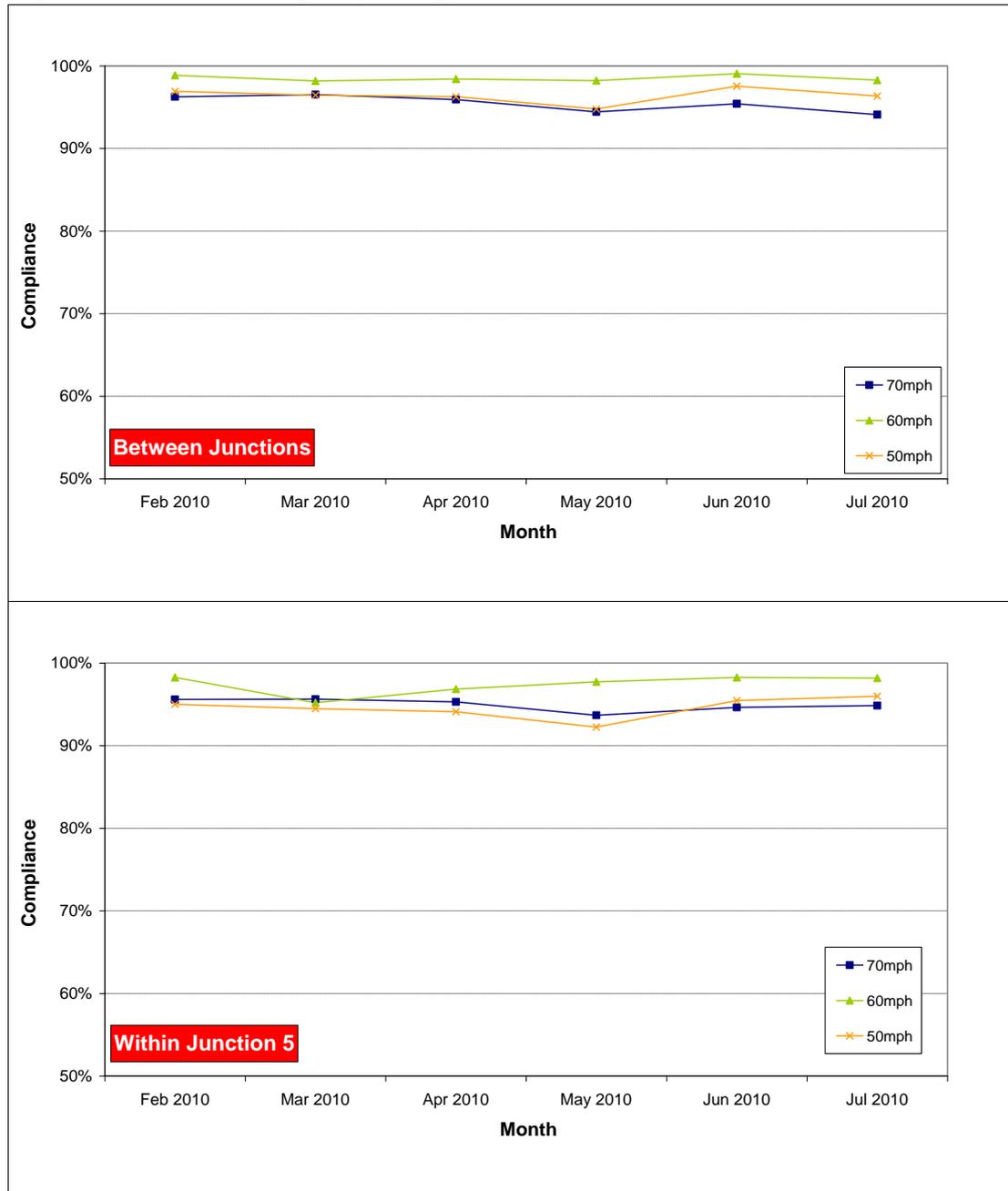
Compliance with speed limits has been assessed by analysing IVD collected from 5 southbound sites positioned between M42 J6 and J4. This data has been combined with the signal settings obtained from HALOGEN to establish the number of compliant vehicles each month.

The level of compliance has been calculated on a monthly basis on the main carriageway between junctions ([J6-J5] and [J5-J4] links combined) and within Junction 5 and is presented in Figure 48. The Association of Chief Police Officers (ACPO) threshold for each speed limit (50 mph to 70 mph) has been used to evaluate all sites. The percentage of compliance is the number of vehicles complying out of the sum of the total number of vehicles at each site per month⁸.

⁸ The ACPO speed limit threshold is defined as the absolute speed limit + 10% + 2 mph

For the purpose of this report, the level of compliance to the 40 mph limit has been excluded as this speed setting is generally only associated with overnight roadworks. A comparison of the before and after cases was not undertaken as IVD was not collected within J5 during the before case period.

Figure 48: Main Carriageway Compliance

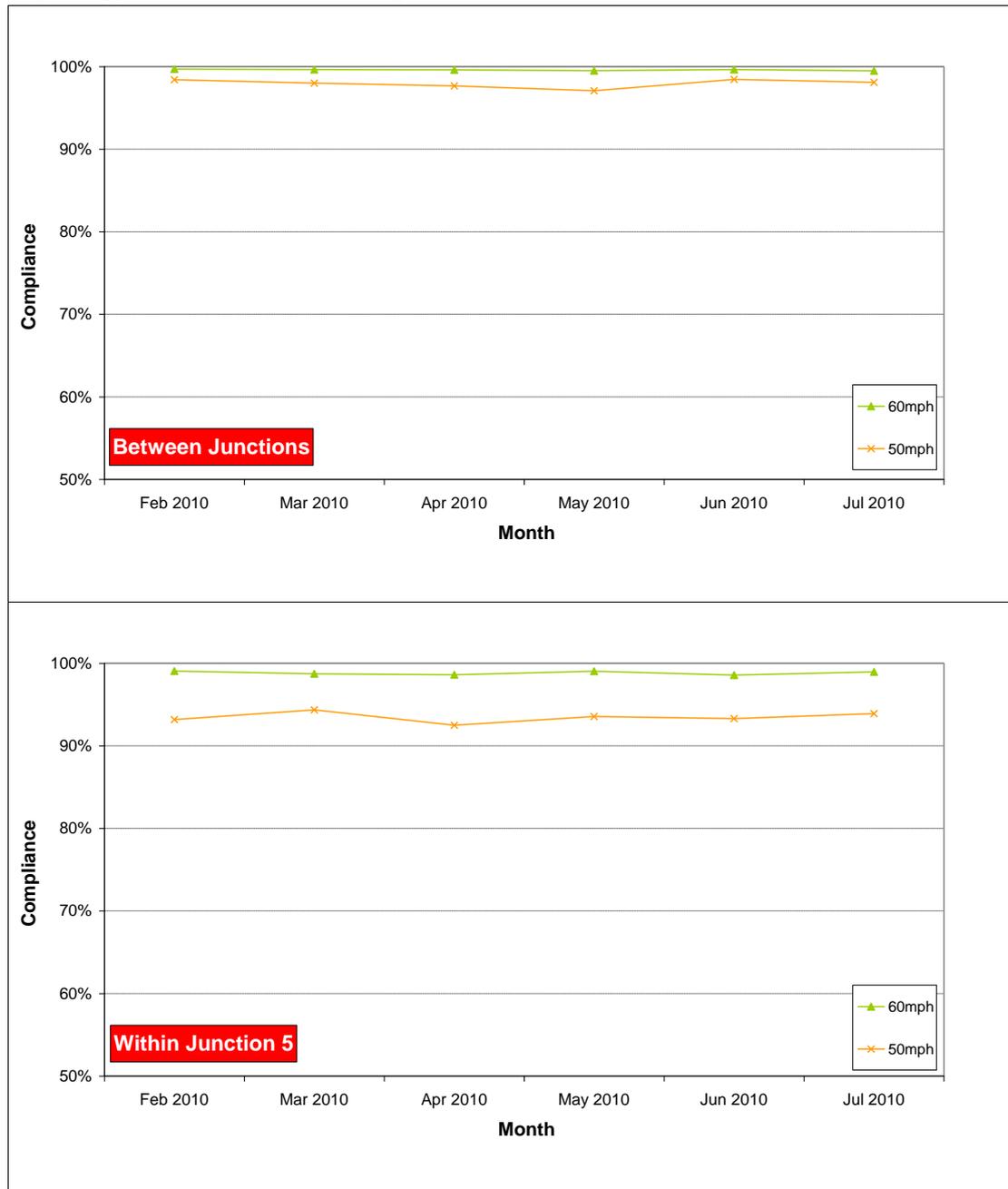


Compliance on the main carriageway between junctions and through the junction was similar. On average, compliance during the study period was 95% (and not lower than 92%) for the 70 mph, 60 mph and 50 mph speed limits. These figures are comparable to the compliance levels reported during previous monitoring exercises undertaken by Mott MacDonald for Highways England (Mott MacDonald, 2009).

Hard Shoulder Compliance

The level of compliance per month on the hard shoulder has also been calculated for the same period considered for the main carriageway compliance and is presented in Figure 49.

Figure 49: Hard Shoulder Compliance



At the ACPO threshold of enforcement, compliance on the hard shoulder between junctions was on average 99.5% and 98% at the 60 mph and 50 mph speed limits respectively. Compliance within Junction 5 was on average 99% and 93% at the 60 mph and 50 mph speed limits respectively. Based on the results presented within Section 6.5 which showed the average speed profiles to be similar, the lower level of compliance observed through the junction is likely to have been present during the before case period.

6.9. User perceptions of TJR

To further understand the findings made from the M42 TJR study, the researcher requested for the user consultation being carried out for the BBMM Phase 2 project to include a section which focused on TJR. 1200 face-to-face interviews were conducted by an external consultant at service stations and Birmingham city centre, and 4 focus group exercises were carried out with frequent users of the BBMM Phase 2 section, commercial drivers and HGV drivers.

The questions specifically relating to the HSR and TJR were prepared by the researcher, and approved by the Highways Agency Project Manager. The copy of the questionnaire issued to the interviewees is found within the appendix, and the key findings from this exercise are summarised below.

6.9.1. Users' awareness and understanding of TJR operations

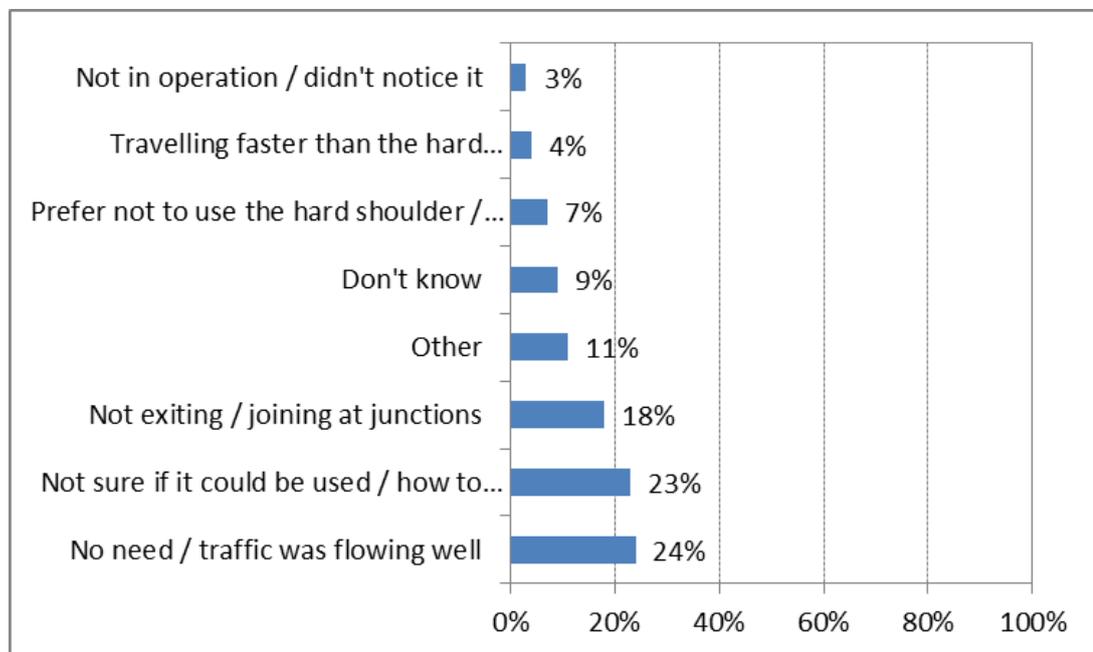
User consultation exercises carried out identified that despite its operational benefits, some motorists are reluctant to use the hard shoulder. The key issues are:

- On-going concern about availability of emergency refuge areas
- A need for more advance notice of changes in lane-use
- lack of confidence in variable mandatory speed limits

From this study, it was identified that only 56% of the respondents were aware that TJR was operational at M6 Junction 10. Of those interviewed, only 41% had used the hard shoulder through the junction. The main reasons behind the low awareness and usage were associated with the lack of understanding, as it was found that frequent users were significantly more aware of TJR (77%) when compared to infrequent users (47%).

The respondents that had not used TJR were asked for their reasons why. The results are summarised in Figure 50.

Figure 50: Reasons for not using the hard shoulder



Although a number of participants felt that the concept was good, there was a general consensus that TJR may confuse road users as its operation differs to the rest of the smart motorway section where only HSR is implemented. The user consultation exercise highlights that there is potentially a need to provide additional driver education and messages displayed on the VMS as participants felt that the lack of understanding could lead to dangerous road conditions.

Some of the following comments were made by the public as a reason for not using TJR:

I don't think people actually understand how to use it at all. (general user)

It's the only one that's like that in the whole scheme. (general user)

Through junction running is presented to road users through roadside signs and road markings; however, the user consultation participants felt that the existing signage/road markings were not sufficient and additional messages through the overhead VMS was required. In particular, many participants acknowledged that they did not understand the road markings at all:

It comes quite suddenly from a solid white line to a broken white line at 300 yards. This is why you need to understand what those lines are for. I get across but lots of people wouldn't see it. (general user)

It does confuse people having two. When it says use hard shoulder for Junction 9 exit only you see people getting over earlier it works. (HGV driver)

The issues identified during the consultation exercise focus are associated with the road users' familiarity with the system, and as such user acceptance may grow with time and perhaps with additional driver education.

Nevertheless these seem to be issues which should be noted for future projects. For example, a commuter who normally travels along the section during peak hours (when HSR is in operation) may assume the hard shoulder to be open during off-peak hours as well. Different measures have been introduced within the countries reviewed to mitigate such problems, notably through the use of VMS, display of the Red-X signal outside of HSR (in the Dutch projects) and the physical closure of the hard shoulder with the movable barriers (France).

The success of smart motorway projects is greatly dependent on road users complying with VMSL and thus requiring accurate, relevant and up-to-date information being communicated to the road users.

6.10. Conclusions

The key findings of the TJR analysis are summarised in the following points:

Throughput

On average there was a 1-2% increase in the observed maximum throughput during TJR when compared to the before case (no-TJR). However, this result was not statistically significant for all sites considered within this study.

Journey Times

Average journey times and variability in average journey times through the section were maintained at a level similar to those in the before case.

Lane Utilisation

Average hard shoulder utilisation increased from 10% to 11.5% on the link upstream of the junction across all day-types.

Average hard shoulder utilisation increased from 12% to 14% on the link downstream of the junction across all day-types.

Average hard shoulder utilisation through the junction was 4.5% of all traffic across all day-types. This indicates that motorists:

- may not be aware of TJR
- may not want to use the hard shoulder through the junction
- may want to use the hard shoulder through the junction but are not sure whether they can

Driver Behaviour

On the M42 TJR site, the video analysis identified a conflict of vehicle movements at the junction diverge, where vehicles exiting the main carriageway directly from lane 1q cross paths with vehicles on the hard shoulder upstream of the junction that are continuing on the hard shoulder through the junction. This has potential safety implications but also indicates that the benefits of TJR could be limited due to lane discipline at this location.

User Consultation

The user consultation exercise identified a potential lack of understanding for this operational regime. Additional driver education and intuitive signage may be required to provide road users with information on how the TJR section should be used.

CHAPTER 7

Changes in traffic demand at the

Birmingham Box

7.1. Introduction

Although the previous sections (CHAPTER 5 and CHAPTER 6) demonstrated the benefits (in terms of traffic conditions) along the BBMM sections as a result of HSR being introduced, the analysis also showed that traffic demand within the scheme extents varied across the considered assessment periods. For example, within the BBMM Phase 2 (BBMM2) study area, a significant increase in traffic demand between the before and after cases was observed which may indicate that motorists were being attracted to the section following the introduction of smart motorways (indicated by the increase in traffic throughput). However, this observation may also be due to other factors (e.g. socioeconomic) which were not assessed as a part of the traffic data analysis carried out in.

This finding was presented to Highways England (then Highways Agency) by the researcher, and led to a separate study to assess the traffic flow on a link-by-link basis for all key links in the Birmingham Box area. Highways England were particularly interested to understand whether the observed increase in traffic demand on the BBMM2 section was a result of traffic being attracted to the smart motorway roads or general traffic growth in the area, as they were particularly interested in understanding whether motorists using their strategic road network would use smart motorways as a part of their journeys.

7.2. Methodology

7.2.1. Data source

Loop data from the MIDAS loops have been used as the primary data source for this assessment. The processed data has been used to determine whether the observed changes in traffic flow (if any) are similar throughout the Birmingham Box or whether there are any particular links and/or sections have shown an increase in demand (i.e. attracting more traffic), and also compared to the changes in motorway traffic within Great Britain for the same period. Note that a data filtration exercise has been undertaken to remove errors in the MIDAS data only, and therefore the dataset analysed includes periods where roadworks and incidents were present.

7.2.2. Assessment period

Average daily traffic (ADT) flow (i.e. 24 hour flow) from MIDAS over a 5 year period between 2006 and 2011 was reviewed as a part of this study. Following a review of data availability and the key dates presented in Figure 5, the following periods were selected to form the analysis:

- 1st April – 31st October 2007 when HSR50 was in operation on the M42-MM section
- 1st April – 31st October 2008 when HSR60 was being introduced on the M42-MM section
- 1st April – 31st October 2009 when BBMM1 was being constructed

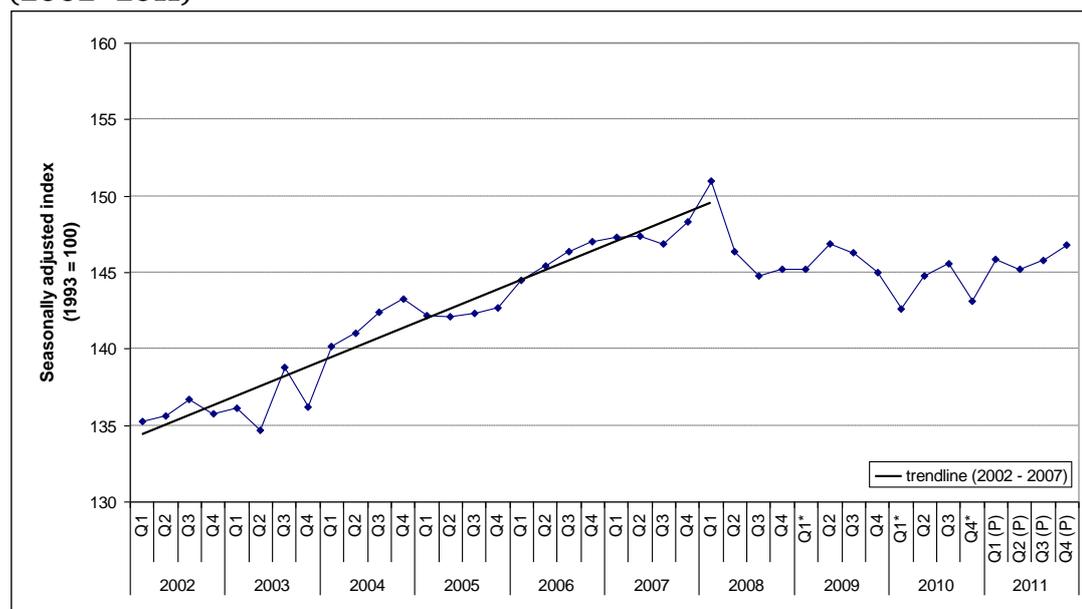
- 1st April – 31st October 2010 when BBMM1 was in operation
- 1st April – 31st October 2011 when BBMM2 was in operation

Data from the same six months of the year in all cases was used to negate the effect of seasonality and associated environmental factors.

7.3. Motorway traffic trends in Great Britain

National statistics data available from the Department for Transport (DfT) has been used to understand the trends in Great Britain traffic. Figure 51 presents the seasonally adjusted indices of motorway traffic in Great Britain between 2002 and 2011.

Figure 51: Motorway traffic in Great Britain, seasonally adjusted indices (2002 -2011)



Source: National Traffic Statistics (Department for Transport, 2009a)
 Note: (P) denotes provisional data, * affected by heavy snowfall.

The figure shows an increase in motorway traffic between 2002 and 2007. The estimated level of road traffic in Great Britain has shown very little change since 2008. The sudden drop in the level of traffic in 2008 is considered by the DfT to be due to an increase in fuel prices and the slowdown of the British economy and recession which in started that year (DfT, 2012).

Based on the figures presented in Figure 51, the year on year change in motorway traffic is presented in Table 17 below.

Table 17: Change in motorway traffic in Great Britain

	2007	2008	2009	2010	2011
Average seasonally adjusted index (percent)	147.5	146.8	145.9	144.0	145.9
Change compared to previous year	--	-0.5%	-0.6%	-1.3%	+1.3%

Source: National Traffic Statistics (DfT, 2009a)

Note: Seasonally adjusted index numbers (1993 = 100)

7.4. Year on year changes in average daily flows

This section presents the results from the traffic data analysis. The findings have been categorised by sections on the Birmingham Box as follows:

- M42-MM section (M42 J3A to J7), forming the east side of the Birmingham Box;
- M6 J3A to J8, forming the north side of the Birmingham Box – includes sections of the Birmingham Smart motorways (BBMM) Phase 1, on the M6 between J4 and J5, and BBMM Phase 3, on the M6 between J5 and J8;
- M6 J8 to J11, includes sections of BBMM Phase 2 on the M6 between J8 and J10A;
- Remaining sections of BBMM Phase 1 (M40 J16 to M42 J3A and M42 between J7 and J9);
- M5 between J5 and M6 J8, forming the west side of the Birmingham Box;
- M42 between J3A and M5 J4A, forming the south side of the Birmingham Box; and
- M6toll sections where traffic data was available.

Changes in ADT flows have been compared year on year for each link considered within this study. The results have been summarised in the tables found in the subsequent sections and the cells have been highlighted as follows to identify whether changes were statistically significant or not.

	Increase in traffic demand is statistically significant
	Increase in traffic demand is not statistically significant
	Decrease in traffic demand is statistically significant
	Decrease in traffic demand is not statistically significant

7.4.1. M42-MM (M42 J3A to J7)



The M42 between J3A and J7 forms the east section of the Birmingham Box. The M42-MM scheme has been in operation on this section of road since September 2006.

The ADT flows between 2007 and 2011 are presented in Table 18.

Table 18: Average daily traffic flow, M42-MM (2007 to 2011)

		Northbound				Southbound			
		M42 [J3A-J4]	M42 [J4-J5]	M42 [J5-J6]	M42 [J6-J7]	M42 [J7-J6]	M42 [J6-J5]	M42 [J5-J4]	M42 [J4-J3A]
2007	ADT	66045	69017	68726	69099	72014	70203	70173	68439
	% change	--	--	--	--	--	--	--	--
2008	ADT	65342	68882	68382	68548	69617	68756	68937	66818
	% change	-1.1%	-0.2%	-0.5%	-0.8%	-3.3%	-2.1%	-1.8%	-2.4%
2009	ADT	63682	66806	66550	66248	68756	66966	67229	65427
	% change	-2.5%	-3.0%	-2.7%	-3.4%	-1.2%	-2.6%	-2.5%	-2.1%
2010	ADT	64753	67072	67200	67269	69989	67521	67560	66006
	% change	1.7%	0.4%	1.0%	1.5%	1.8%	0.8%	0.5%	0.9%
2011	ADT	64181	67627	67743	67148	69652	68054	67816	65272
	% change	-0.9%	0.8%	0.8%	-0.2%	-0.5%	0.8%	0.4%	-1.1%

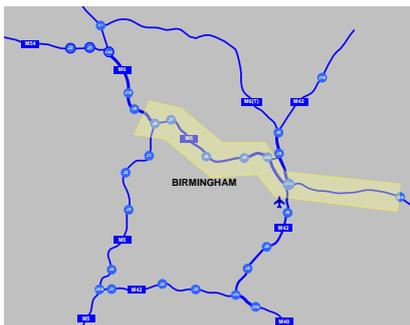
The findings are summarised as follows:

- A decrease in traffic demand was observed across all links of this section in both northbound and southbound directions between 2007 and 2008. This change was in line with the trends in motorway traffic reported by the DfT for Great Britain. Greater reductions were observed in the southbound direction where there was a statistically significant decrease in traffic demand on the [J7-J6] and [J4-J3A] links.
- A decrease in traffic demand was observed across all links of this section in both northbound and southbound directions between 2008 and 2009.

This change was slightly greater than that reported by the DfT for Great Britain. The decrease was statistically significant on all northbound links and on the [J6-J5] and [J5-J4] southbound links.

- An increase in traffic demand was observed on all links of this section between 2009 and 2010, however, was not statistically significant. This was not in line with the trends in motorway traffic reported by the DfT where a reduction was observed over the same period.
- ADT flows increased on the [J4-J5] and [J5-J6] links and decreased on the [J3A-J4] and [J6-J7] links between 2010 and 2011. The observed changes were not statistically significant on all links.
- The ADT flows for 2010 and 2011 were lower than the ADT flows observed in 2007 and 2008.

7.4.2. M6 J3A to J8



The M6 between J3A and J8 forms the north segment of the Birmingham Box and includes the BBMM Phase 1 (BBMM1) and BBMM Phase 3 (BB3MM) sections. BBMM1 has been in operation on this road since November 2009. Data was not available on the M6 between J4 and J5 for 2009 due to BBMM1 construction. MIDAS data was also not available on the M6 [J3A-J4] northbound and southbound links so traffic data from the Highways Agency Traffic Information System (HATRIS) Traffic Database (TRADS) was used where possible.

The ADT flows between 2007 and 2011 are presented in Table 19.

Table 19: Average daily traffic flow, M6 J3A to J8 (2007 to 2011)

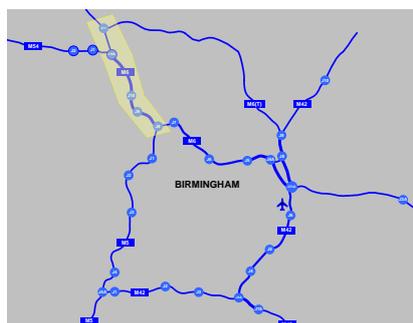
		Northbound						Southbound					
		M6 [J3A-J4]	M6 [J4-J4A]	M6 [J4A-J5]	M6 [J5-J6]	M6 [J6-J7]	M6 [J7-J8]	M6 [J8-J7]	M6 [J7-J6]	M6 [J6-J5]	M6 [J5-J4A]	M6 [J4A-J4]	M6 [J4-J3A]
2007	ADT	46766	54555	67518	59666	67488	72358	64948	62878	58639	69363	37388	46356
	% change	--	--	--	--	--	--	--	--	--	--	--	--
2008	ADT	47293	54677	68676	61345	68708	72121	67365	65376	62687	72080	38709	47627
	% change	1.1%	0.2%	1.7%	2.8%	1.8%	-0.3%	3.7%	4.0%	6.9%	3.9%	3.5%	2.7%
2009	ADT	46247	--	--	57968	67758	70430	66777	62752	57321	--	--	45998
	% change	-2.2%	--	--	-5.5%	-1.4%	-2.3%	-0.9%	-4.0%	-8.6%	--	--	-3.4%
2010	ADT	--	56702	71788	59043	68083	70899	67376	64860	57446	71781	38285	--
	% change	--	--	--	1.9%	0.5%	0.7%	0.9%	3.4%	0.2%	--	--	--
2011	ADT	--	57192	73364	61802	70168	72257	70270	67065	61876	74897	40218	--
	% change	--	0.9%	2.2%	4.7%	3.1%	1.9%	4.3%	3.4%	7.7%	4.3%	5.1%	--

data from TRADS
 data not available due to BBMM1 construction

The findings are summarised as follows:

- An increase in traffic demand was observed between 2007 and 2008 on all links of this section except for the [J7-J8] northbound link. This change was not in line with the declining trend in motorway traffic reported by the DfT for Great Britain. The observed increases in the southbound direction were statistically significant except for the [J4-J3A] link. The observed changes in the northbound direction were not statistically significant.
- A decrease in ADT flows was observed between 2008 and 2009 on all links of this section where traffic data was available. This was in line with the declining trend in motorway traffic reported by the DfT for Great Britain; however, it is considered that this would have been largely attributed to the construction of BBMM1 during this period.
- An increase in traffic demand was observed between 2009 and 2010 on all links of this section where traffic data was available. It is considered that this increase was due to the opening of BBMM1 on this section.
- An increase in traffic demand was observed between 2010 and 2011 on all links of this section where traffic data was available. It is considered that this increase was due to the increase in traffic demand observed from the BBMM2 and M5 northbound sections..
- Overall, the ADT flows observed in 2010 and 2011 were higher than the ADT flows observed in 2007 and 2008.

7.4.3. M6 J8 to 11



The M6 between J8 and J11 extends from the northeast end of the Birmingham Box towards Manchester and the north end of the M6toll. This section includes the BBMM Phase 2 section which has been in operation since March 2011. Data was not available on the M6 between J8 and J10 for 2010 due to BBMM2 construction.

The ADT flows between 2007 and 2011 are presented in Table 20

Table 20: Average daily traffic flow, M6 J8 to J11 (2007 to 2011)

		Northbound				Southbound			
		M6 [J8-J9]	M6 [J9-J10]	M6 [J10-J10A]	M6 [J10A-J11]	M6 [J11-J10A]	M6 [J10A-J10]	M6 [J10-J9]	M6 [J9-J8]
2007	ADT	78786	76736	69322	49171	46390	65704	74607	74861
	% change	--	--	--	--	--	--	--	--
2008	ADT	80319	76899	70953	50739	47365	66838	76334	78105
	% change	1.9%	0.2%	2.4%	3.2%	2.1%	1.7%	2.3%	4.3%
2009	ADT	79697	76432	70998	50043	47004	67389	76502	80117
	% change	-0.8%	-0.6%	0.1%	-1.4%	-0.8%	0.8%	0.2%	2.6%
2010	ADT	--	--	68665	47828	42233	61186	--	--
	% change	--	--	-3.3%	-4.4%	-10.2%	-9.2%	--	--
2011	ADT	84874	82148	73342	49955	48127	69773	79828	85740
	% change	--	--	6.8%	4.4%	14.0%	14.0%	--	--

Note: 2007 missing half of study period due to loop availability/reliability data not available due to BBMM2 construction

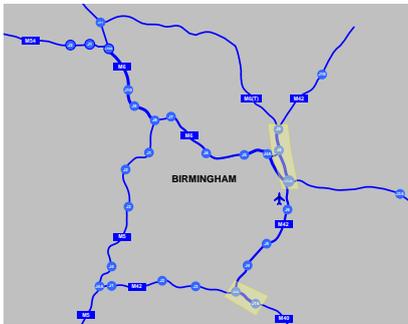
The findings are summarised as follows:

- An increase in traffic demand was observed between 2007 and 2008 on all links of this section in both northbound and southbound directions. This was not in line with the declining trend in motorway traffic reported by the DfT for Great Britain.
- The change in ADT flows between 2008 and 2009 was not statistically significant between 2008 and 2009 on all links of this section except for M6 [J9-J8] in the southbound direction where a statistically significant increase in traffic demand was observed.
- A statistically significant decrease in traffic demand was observed between 2009 and 2010 on all links of this section where traffic data was

available. This was in line with the declining trend in motorway traffic reported by the DfT over the same period; however, it is considered that this would have been largely attributed to the construction of BBMM2 during this period.

- A statistically significant increase in traffic demand was observed between 2010 and 2011 on all links of this section where traffic data was available. This was in line with the trend in motorway traffic where an increase was reported by the DfT for Great Britain over the same period; however, it is considered that the opening of BBMM2 on this section in 2011 would have also had an effect on flows.
- Similar to the M6 between J3A and J8, the ADT flows observed in 2010 and 2011 are higher than the ADT flows observed in 2007 and 2008. It is considered that the observed increase in traffic demand on this section contributed to the statistically significant increase in ADT flows observed on the M6 between J8 and J4 southbound and M5 between J1 and M6 J8 southbound in 2011.

7.4.4. *BBMM1 (M40 J16 to M42 J3A and M42 J7 to J9)*



The M40 between J16 and M42 J3A and the M42 between J7 and J9 form other sections of BBMM1. Controlled motorways has been in operation on the M40 between J16 and M42 J3A in the northbound direction and on the M42 links in both northbound and southbound directions since November 2009.

The ADT flows between 2007 and 2011 are presented in Table 21.

Table 21: Average daily traffic flow, M40 J16 to M42 J3A and M42 J7 to J9 (2007 to 2011)

		Northbound			Southbound		
		M40 J16 - M42 J3A	M42 [J7-J8]	M42 [J8-J9]	M42 [J9-J8]	M42 [J8-J7]	M42 J3A - M40 J16
2007	ADT	47941	53078	57651	54337	59231	47294
	% change	--	--	--	--	--	--
2008	ADT	47208	51812	55559	50319	55657	46634
	% change	-1.5%	-2.4%	-3.6%	-7.4%	-6.0%	-1.4%
2009	ADT	45633	50595	55408	51737	56237	45149
	% change	-3.3%	-2.3%	-0.3%	2.8%	1.0%	-3.2%
2010	ADT	46288	51942	55349	52274	57275	45895
	% change	1.4%	2.7%	-0.1%	1.0%	1.8%	1.7%
2011	ADT	46690	49140	52666	49100	56794	46401
	% change	0.9%	-5.4%	-4.8%	-6.1%	-0.8%	1.1%

Overall, the ADT flow observed on this section of road in 2011 was lower than the ADT flows observed in 2007 and 2008. The findings are summarised as follows:

M42 J7 to J9

- In the northbound direction, there was a year on year decrease in ADT flow between 2007 and 2011 except for the [J7-J8] northbound link between 2009 and 2010. It is considered that the observed changes between 2007 and 2008 would have been due to the statistically significant decrease in traffic demand observed on the M42-MM northbound section over this period. The observed decrease between 2008 and 2009 would have been largely attributed to the construction of BBMM1 on the M6 J4 to J5 section during this period.
- In the southbound direction, there was a statistically significant decrease in traffic demand between 2007 and 2008. The observed increase in traffic demand observed between 2008 and 2010 was not statistically significant.

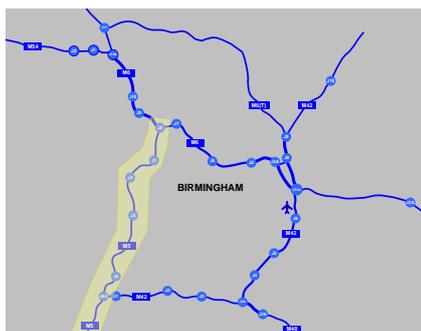
M40 J16 to M42 J3A

- A year on year decrease in ADT flows were observed between 2007 and 2009. This was in line with the trend in motorway traffic flow where a decrease was reported by the DfT for Great Britain over the same period.
- It is considered that in the northbound direction, this reduction contributed to the observed reduction on the M42-MM and M42 between M5 J4A and J3A southbound directions over the same period. It is considered that in the northbound direction, this reduction contributed to

the observed reduction on the M42-MM and M42 between J3A and M5 J4A southbound directions over the same period.

- A year on year increase in ADT flows were observed between 2009 and 2011, however, these were not statistically significant.

7.4.5. M5 between J5 and M6 J8



The M5 between J5 and M6 J8 forms the west section of the Birmingham Box.

The ADT flows between 2007 and 2011 are presented in Table 22.

Table 22: Average daily traffic flow, M5 between J5 and M6 J8 (2007 to 2011)

		Northbound						Southbound					
		M5 [J5-J4A]	M5 [J4A-J4]	M5 [J4-J3]	M5 [J3-J2]	M5 [J2-J1]	M5 J1- M6 J8	M6 J8-M5 J1	M5 [J1-J2]	M5 [J2-J3]	M5 [J3-J4]	M5 [J4-J4A]	M5 [J4A-J5]
2007	ADT	61034	47640	45614	47090	51553	52891	53017	49461	45666	44406	46029	60448
	% change	--	--	--	--	--	--	--	--	--	--	--	--
2008	ADT	60548	47388	45277	47259	51596	52490	55057	52688	47462	45529	47057	60540
	% change	-0.8%	-0.5%	-0.7%	0.4%	0.1%	-0.8%	3.8%	6.5%	3.9%	2.5%	2.2%	0.2%
2009	ADT	60331	46712	45630	46565	50893	51899	55153	52848	46544	46331	46979	60183
	% change	-0.4%	-1.4%	0.8%	-1.5%	-1.4%	-1.1%	0.2%	0.3%	-1.9%	1.8%	-0.2%	-0.6%
2010	ADT	58182	44924	43444	44168	48701	49089	53479	50971	44561	43255	44963	59224
	% change	-3.6%	-3.8%	-4.8%	-5.1%	-4.3%	-5.4%	-3.0%	-3.6%	-4.3%	-6.6%	-4.3%	-1.6%
2011	ADT	58011	44650	43039	45201	52274	54179	55466	53640	45413	44439	44647	58414
	% change	-0.3%	-0.6%	-0.9%	2.3%	7.3%	10.4%	3.7%	5.2%	1.9%	2.7%	-0.7%	-1.4%

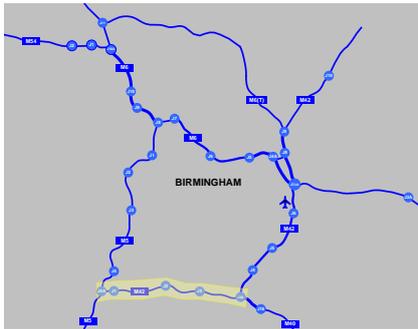
The findings are summarised as follows:

- The year on year changes in ADT flows between 2007 and 2009 were not statistically significant except for the M5 [J1-J2] and [J2-J3] southbound links between 2007 and 2008.
- A statistically significant decrease in ADT flows was observed on this section between 2009 and 2010 except on the M6 J8 to M5 J1 southbound link. It is considered that this decrease would have been largely attributed to the construction of BBMM2 during this period.
- A statistically significant increase in ADT flows was observed on the M5 between J2 and M6 J8 between 2010 and 2011. It is considered that this

was due to the increase in traffic demand observed on the M6 sections following the introduction of BBMM2.

- Overall, the ADT flows observed on the M5 between J2 and J5 in 2011 were lower than the ADT flows observed in 2007 and 2008. The ADT flows observed on the M5 between J2 and M6 J8 in 2011 were higher than the ADT flows observed in 2007 and 2008.

7.4.6. M42 between J3A and M5 J4A



The M42 between J3A and M5 J4A forms the south section of the Birmingham Box.

The ADT flows between 2007 and 2011 are presented in Table 23.

Table 23: Average daily traffic flow, M42 between J3A and M5 J4A (2007 to 2011)

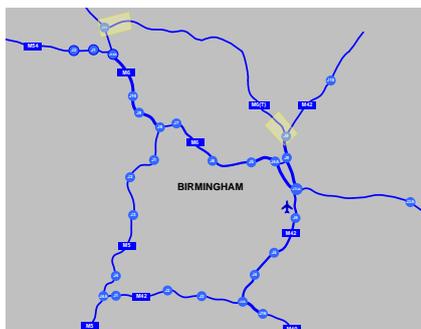
		Northbound				Southbound			
		M5 J4A-M42 J1	M42 [J1-J2]	M42 [J2-J3]	M42 [J3-J3A]	M42 [J3A-J3]	M42 [J3-J2]	M42 [J2-J1]	M42 J1-M5 J4A
2007	ADT	40139	47221	49505	54964	56207	51356	48876	42488
	% change	--	--	--	--	--	--	--	--
2008	ADT	40738	47913	49933	55139	55670	50732	48049	42020
	% change	1.5%	1.5%	0.9%	0.3%	-1.0%	-1.2%	-1.7%	-1.1%
2009	ADT	39854	47112	49393	54903	55139	49941	47733	41240
	% change	-2.2%	-1.7%	-1.1%	-0.4%	-1.0%	-1.6%	-0.7%	-1.9%
2010	ADT	39766	46958	49108	54747	54913	49395	47126	40790
	% change	-0.2%	-0.3%	-0.6%	-0.3%	-0.4%	-1.1%	-1.3%	-1.1%
2011	ADT	39469	46677	48979	54672	54734	49195	46961	40554
	% change	-0.7%	-0.6%	-0.3%	-0.1%	-0.3%	-0.4%	-0.4%	-0.6%

The findings are summarised as follows:

- Between 2007 and 2008, a small increase in traffic demand was observed in the northbound direction.
- Traffic decreased year on year on this section of road between 2008 and 2011 in the northbound direction, and between 2007 and 2011 in the southbound direction.

- Overall, traffic levels have decreased but there was no statistically significant change in traffic demand on this section of road throughout the study period (year on year).

7.4.7. M6toll



The M6toll, introduced in 2003, extends between M6 J11 and M42 J9 and is found to the north of the Birmingham Box.

Results from this road should be viewed with care as limited data was available.

The ADT flows between 2007 and 2011 are presented in Table 24.

Table 24: Average daily traffic flow, M6toll (2007 to 2011)

		M6 J11		M42 J9	
		M6toll to M6	M6 to M6toll	M42 to M6toll	M6 toll to M42
2007	ADT	--	--	21206	25454
	% change	--	--	--	--
2008	ADT	--	--	17852	23534
	% change	--	--	-15.8%	-7.5%
2009	ADT	--	--	17464	25077
	% change	--	--	-2.2%	6.6%
2010	ADT	18286	15862	19201	24047
	% change	--	--	9.9%	-4.1%
2011	ADT	18301	13372	15625	21660
	% change	0.1%	-15.7%	-18.6%	-9.9%

Note that flow levels on this section were estimated using traffic data from adjacent links and slip roads. Therefore statistical analysis was not undertaken and it was not possible to ascertain whether the change in traffic demand on the BBMM sections contributed to the observations made on the M6toll sections considered within this study.

Based on the very limited data the findings are summarised as follows:

- At M6 J11, a decrease in traffic travelling from the M6 to the M6toll was observed between 2010 and 2011. Although this reduction may be attributed to the statistically significant increase in traffic demand

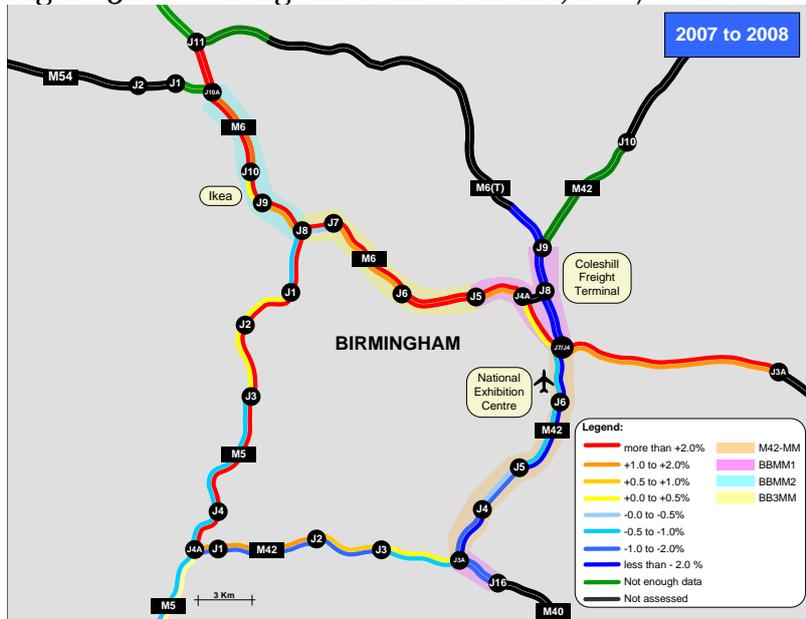
observed on the M6 between J8 and J11 over the same period, additional traffic data and/or longer monitoring periods would be required to validate this observation.

- At M42 J9, a decrease in ADT flows was observed year on year except for the period between 2008 and 2009 for traffic travelling from the M6 toll to the M42.

7.5. Summary of findings

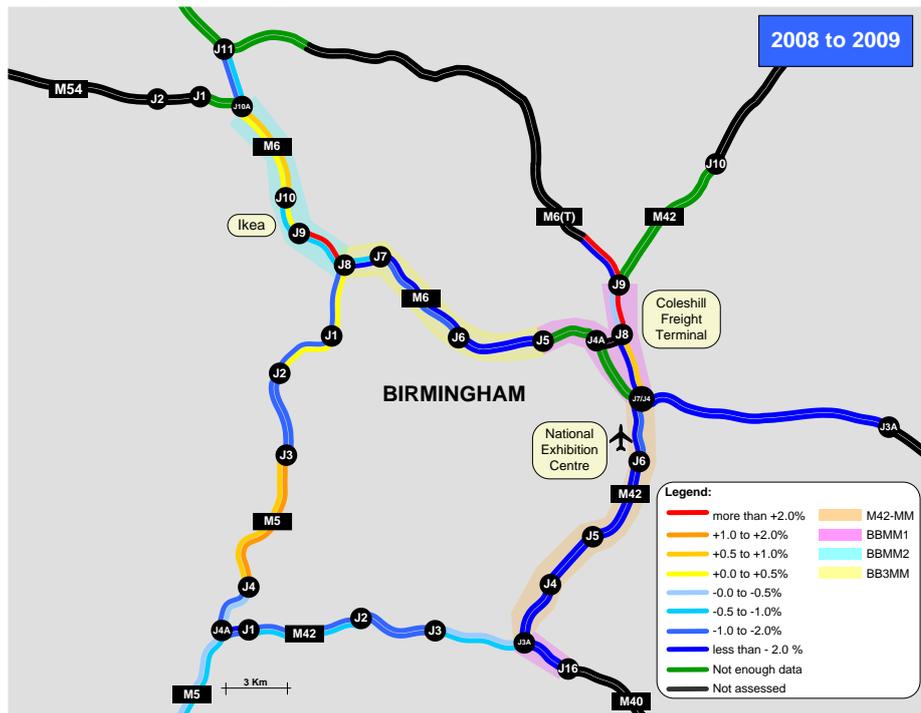
The changes in traffic demand in the Birmingham Box reported in Section 1.1 have been summarised in the figures presented in this section.

Figure 52: Change in traffic demand, 2007 to 2008



- HSR60 was introduced on the M42-MM section during 2008.
- The DfT reported a decrease of motorway traffic in Great Britain over this period, however, an increase in traffic demand was observed on the M6, M5 southbound and M42 northbound (M5 J4A to J3A) links.

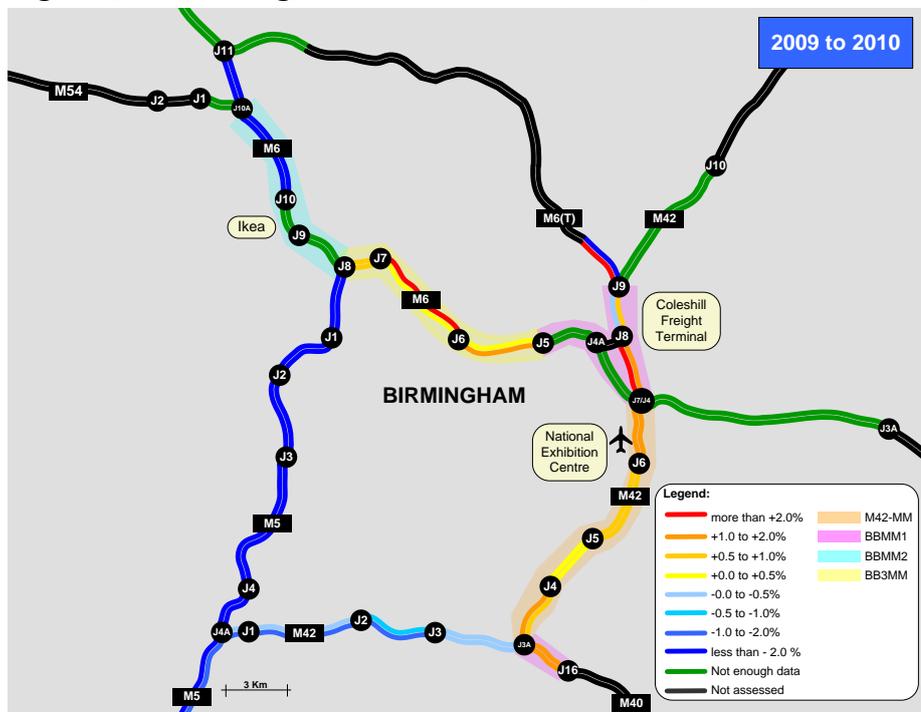
Figure 53: Change in traffic demand, 2008 to 2009



- Construction of BBMM1 was ongoing during this period.

Reduction in traffic demand was observed on most links on the Birmingham Box area.

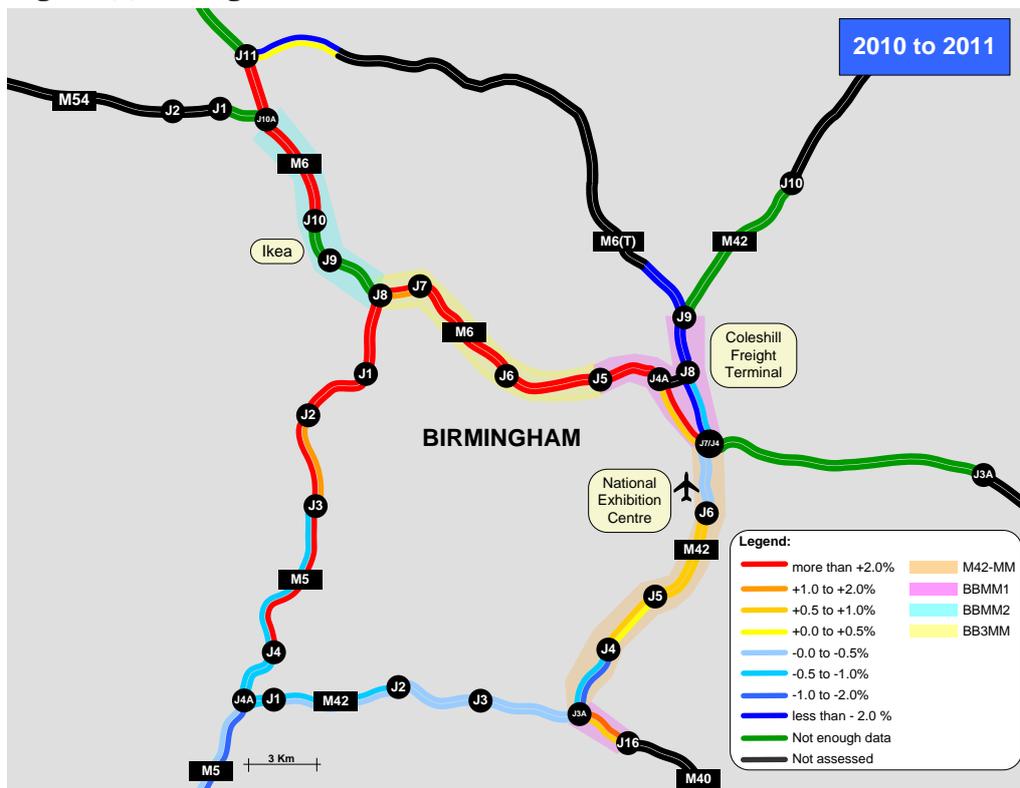
Figure 54: Change in traffic demand, 2009 to 2010



- BBMM1 was introduced during this period.
- Construction of BBMM2 was ongoing during this period.
- An increase in traffic demand was observed on the BBMM1 section.

A reduction in traffic demand was observed on the BBMM2 section

Figure 55: Change in traffic demand, 2010 to 2011



- BBMM2 was introduced during this period.
- An increase in traffic demand was observed on the M6 following the introduction of BBMM2.
- Traffic levels observed on the M42 and M5 between J2 and J5 were lower than the ADT flows observed in 2007 and 2008.
- Traffic levels observed on the M6 between J4 and J11 and M5 between J2 and M6 J8 were higher than the ADT flows observed in 2007 and 2008.

7.6. Conclusions

The study has evaluated year on year changes in ADT flows in the Birmingham Box area for the period between 2007 and 2011. The key findings are summarised into the following points:

- A reduction in ADT flows were observed on the adjacent links of the BBMM1 and BBMM2 sections during their respective construction periods. However, ADT flows increased post-construction on these sections.
- ADT flows observed on the M42 links and M5 links between J2 and J5 in 2011 were lower than the ADT flows observed in 2007 and 2008.

- ADT flows on the M6 between J4 and J11 the M5 between J2 and M6 J8 in 2011 were higher than the ADT flows observed in 2007 and 2008. The year on year changes in ADT flows on the M6 between J4 and J11 were generally not in line with the figures reported by the DfT for Great Britain, and showed a year on year increase in traffic levels between 2007 and 2010 (excluding the construction period). The observed increase in traffic levels between 2010 and 2011 were also higher than the figures reported by the DfT.

Overall, the decline in ADT flows shown during construction of BBMM 1&2 and the increase in ADT flows shown post-construction indicates that motorists who may have been bypassing the relative sections during construction may be returning to the section. This observation, coupled with the slight reduction in traffic levels observed on the other sections of the Birmingham Box indicates that the M6 is the key route through the West Midlands area and has attracted traffic over the assessment period.

CHAPTER 8

Capacity Study

8.1. Methodology

This study has been undertaken by isolating days on which flow-breakdowns have been observed and identifying the traffic characteristics within each occurrence. These days were chosen from the period October 2006 (shortly after the introduction of HSR) to May 2009, based on the following criteria:

An increase in journey time was observed when compared to normal days⁹. This was based on the findings from the ATM 12 month report and assessments of HSR60 (Sultan et al, 2008. Ogawa et al, 2009), where the following values were identified to represent average journey times of non-capacity days ¹⁰:

Table 25: Average Journey Times of Non-Capacity Days

Operational Regime	Average Journey Time(min:sec)	
	Northbound	Southbound
HSR50	10:55	11:08
HSR60	10:26	10:35

⁹ Normal days represent days which showed no congestion and HSR was operational.

¹⁰ This was quantified as the average journey times during weekdays over the AM-Peak (06:00 – 11:00 hrs) and PM-Peak (16:00 – 21:00 hrs) periods.

No incidents were observed at the time of congestion upstream and/or downstream of the site. Motorway Traffic Viewer (MTV) plots, HALOGEN data and NTCC reports were used to identify that the congestion was not due to an incident or accident.

- HSR was in operation at the time of congestion. This was verified through the use of MTV plots and HALOGEN data.

Following the identification of the capacity days, “non-capacity” days were identified to formulate a reference case. These days were identified based on the following criteria:

- No incidents were observed during the peak periods upstream or downstream of the junction
- HSR was in operation
- Traffic flows (i.e. level of demand) similar to that of the capacity days identified
- Similar day-types and time of year (to eliminate the effect of seasonality)

The analysis investigated specific traffic indicators including traffic flow, percentage of Heavy Goods Vehicles (HGV%) and lane utilisation to understand the situations at which flow-breakdown occurred.

8.1.1. Data Sets

Table 26 lists the days which were identified as “capacity days” in this study:

Table 26: List of Capacity Days

Date	Direction	Junction	OR	Time of Congestion	
				start	end
16/11/06	NB	J6	HSR50	15:45	18:30
26/01/07	SB	J6	HSR50	15:00	17:50
09/03/07	NB	J6	HSR50	15:45	17:45
29/10/07	NB	J6	HSR50	16:45	17:30
01/11/07	NB	J6	HSR50	16:20	18:30
28/11/07	NB	J6	HSR50	16:20	19:30
29/11/07	NB	J6	HSR50	16:20	17:40
06/12/07	NB	J6	HSR50	16:20	18:30
16/10/08	NB	J6	HSR60	16:25	18:45
23/10/08	NB	J6	HSR60	16:45	18:45
14/11/08	NB	J6, J4	HSR60	16:10	18:30
28/11/08	NB	J6	HSR60	15:20	17:20
05/12/08	SB	J4	HSR60	14:30	17:00
12/12/08	NB	J6	HSR60	15:20	17:30
19/02/09	NB	J6	HSR60	16:20	19:00
20/02/09	NB	J6	HSR60	15:40	19:00
05/03/09	NB	J6	HSR60	16:20	18:00
09/04/09	NB	J6	HSR60	16:20	18:40

The majority of “capacity” days identified were observed during the PM peak at the M42 Junction 6 northbound merge. This junction is a two-lane tiger tail merge and as identified in Section 1.3, is characterised by high daily traffic flows providing the main link to Birmingham International Airport and the National Exhibition Centre (NEC).

This study focuses on the M42 Junction 6 as it gives the best data set. This would also eliminate the variability of results associated with physical road features (e.g. road geometry, existing infrastructure).

8.1.2. Data Measurements

The analysis approach is to study the ramp flows, upstream and downstream traffic conditions to investigate the flow-breakdown mechanisms and factors which have a significant effect on motorway capacity under Smart motorways operation. Therefore, suitable locations at which these parameters are measured have been identified.

A capacity study undertaken by Hounsell et al (1994) identified that flow-breakdown was found to occur at most sites at a point between the end of the merge and up to 2 km downstream. MTV plots were used to validate the selection of loops to support the assessment. The following loops were used for this study:

Table 27: List of MIDAS Loops Used for Capacity Analysis

Loop Location	Loop Reference
Upstream/within congestion (0.1 km upstream of junction)	M42/6427A
Downstream of Congestion (i.e. near queue discharge) (1.4 km downstream of junction)	M42/6442A
Ramp Flow	M42/6428K

The data set summarised in Table 26 has shown that congestion at this site was generally observed between 16:00 – 18:00 hours. Therefore this study has focused on the time between 15:00 – 19:00 hours to include the build-up and decay of traffic flows during periods where congestion was observed.

8.2. Data Analysis

Following the findings from the previous section, speed/flow plots and profiles were produced at 15 minute intervals for each capacity day. The maximum downstream flow observed before flow-breakdown and during queue discharge has been studied and are as summarised in Table 28 (during queue discharge) and Table 29 (before flow-breakdown).

Table 28: Summary of Capacity Days (during queue discharge)

Date	OR	Time of Congestion		max downstream flow during queue discharge		observations made during max downstream flow at queue discharge					
		Start	End	time observed	flow (veh/hr)	upstream flow (veh/hr)	ramp flow (veh/hr)	ramp %	HGV flow (veh)	HGV%	HS Util%
16/11/06	HSR50	15:45	18:30	16:15	6768	4688	2024	29.9%	712	10.5%	14.9%
09/03/07	HSR50	15:45	17:45	17:15	6732	4712	2052	30.5%	448	6.7%	16.2%
29/10/07	HSR50	16:45	17:30	17:30	6896	4460	2376	34.5%	520	7.5%	15.8%
01/11/07	HSR50	16:20	18:30	16:30	7144	4568	2600	36.4%	644	9.0%	16.3%
28/11/07	HSR50	16:20	19:30	16:30	6544	4532	2052	31.4%	536	8.2%	16.0%
29/11/07	HSR50	16:20	17:40	16:30	6980	4924	2128	30.5%	628	9.0%	14.8%
06/12/07	HSR50	16:20	18:30	17:45	6088	4340	1700	27.9%	504	8.3%	18.1%
16/10/08	HSR60	16:25	18:45	16:45	6792	4828	1900	28.0%	548	8.1%	14.7%
23/10/08	HSR60	16:45	18:45	17:30	6888	4984	1848	26.8%	444	6.4%	17.5%
14/11/08	HSR60	16:10	18:30	16:15	6564	4628	1800	27.4%	440	6.7%	12.6%
28/11/08	HSR60	15:20	17:20	17:15	6356	4420	1964	30.9%	260	4.1%	14.9%
12/12/08	HSR60	15:20	17:30	17:45	5976	4296	1336	22.4%	308	5.2%	12.3%
19/02/09	HSR60	16:20	19:00	16:30	7036	4840	2224	31.6%	536	7.6%	14.2%
20/02/09	HSR60	15:40	19:00	16:45	6628	5020	1640	24.7%	408	6.2%	14.5%
05/03/09	HSR60	16:20	18:00	16:30	7132	4832	2308	32.4%	604	8.5%	17.4%
09/04/09	HSR60	16:20	18:40	16:30	6840	5304	1744	25.5%	380	5.6%	15.0%

Table 29: Summary of Capacity Days (before congestion)

Date	max downstream flow observed before congestion		observations made during max downstream flow before congestion					
	time observed	flow (veh/hr)	upstream flow (veh/hr)	ramp flow (veh/hr)	ramp %	HGV flow (veh)	HGV%	HS Util%
16/11/06	15:30	6108	4856	1464	23.97%	964	15.78%	12.97%
09/03/07	15:30	6068	4648	1464	24.13%	552	9.10%	6.99%
29/10/07	16:45	6364	4612	1976	31.05%	724	11.38%	15.34%
01/11/07	16:15	7432	5224	2372	31.92%	772	10.39%	14.10%
28/11/07	16:15	6736	4760	2144	31.83%	620	9.20%	13.18%
29/11/07	16:15	6516	4576	2120	32.54%	620	9.52%	15.35%
06/12/07	16:15	5908	4264	1844	31.21%	644	10.90%	16.93%
16/10/08	16:15	6944	5028	1996	28.74%	620	8.93%	15.09%
23/10/08	16:30	6672	4940	1712	25.66%	532	7.97%	14.03%
14/11/08	15:45	6292	4728	1504	23.90%	532	8.46%	11.57%
28/11/08	15:15	6448	5128	1332	20.66%	596	9.24%	14.58%
12/12/08	14:45	5736	4608	1312	22.87%	616	10.74%	3.84%
19/02/09	16:15	7000	4852	2224	31.77%	552	7.89%	15.71%
20/02/09	15:30	6584	5036	1516	23.03%	352	5.35%	13.43%
05/03/09	15:45	5896	4328	1668	28.29%	588	9.97%	13.98%
09/04/09	16:15	6744	5248	1596	23.67%	560	8.30%	12.34%

It can be seen that the maximum flow before congestion occurred exceeded that during congested conditions on 4 days (01/11/07, 28/11/07, 16/10/08, and 28/11/08). This lends some support to the form of the curve in

Figure 23 where the 'unstable' flow rate is shown to exceed the queue discharge rate. However, taking all days together, the average throughput during congestion (6710 veh/hr) exceeded the average throughput just before congestion occurred (6466 veh/hr) by approximately 4%. Given that the queue discharge flow rate is consistent with capacity measurements in other situations (e.g. at traffic signals), then subsequent analysis of 'capacity days' has been based on the queue discharge rates only.

For the non-capacity days, the time at which maximum flow had been observed was recorded (as flow-breakdown was not observed on these days). Summary of non-capacity days are as summarised in Table 30.

Based on this information, the following indicators were studied to investigate motorway capacity under Smart motorways operation:

- Changes in traffic demand (upstream and downstream)
- Traffic composition (HGV%)
- Hard shoulder utilisation (HS Util %)
- Ramp demand and proportion of ramp flow (ramp %)

Table 30: Summary of Non-Capacity Days (max observed)

Date	OR	max downstream flow observed		observations made during max downstream flow					
		time observed	flow (veh/hr)	upstream flow (veh/hr)	ramp flow (veh/hr)	ramp %	HGV flow (veh)	HGV%	HS Util%
15/11/06	HSR50	17:15	6272	4160	1996	31.8%	468	7.5%	13.9%
06/03/07	HSR50	17:30	6868	4632	2008	29.2%	516	7.5%	14.4%
24/10/07	HSR50	17:15	6892	5196	1744	25.3%	548	8.0%	13.5%
07/11/07	HSR50	17:30	7100	4952	2180	30.7%	480	6.8%	15.2%
21/11/07	HSR50	17:15	6816	4792	1848	27.1%	604	8.9%	13.9%
03/12/07	HSR50	17:00	6064	4500	1516	25.0%	664	10.9%	13.7%
04/12/07	HSR50	16:30	6560	4840	1776	27.1%	800	12.2%	15.8%
04/11/08	HSR60	16:15	6620	4520	2276	34.4%	676	10.2%	15.8%
05/11/08	HSR60	17:45	6524	4672	1744	26.7%	368	5.6%	13.2%
11/11/08	HSR60	16:30	6644	4908	1776	26.7%	600	9.0%	15.2%
16/12/08	HSR60	16:30	6136	4300	1808	29.5%	588	9.6%	15.8%
17/12/08	HSR60	16:45	6296	4852	1556	24.7%	520	8.3%	11.8%
26/02/09	HSR60	16:30	7012	5036	2052	29.3%	576	8.2%	14.2%
27/02/09	HSR60	16:45	6740	5076	1560	23.1%	432	6.4%	12.6%
10/03/09	HSR60	17:30	6660	4808	1764	26.5%	340	5.1%	13.3%
02/04/09	HSR60	17:00	6668	4804	1820	27.3%	536	8.0%	13.4%

8.2.1. Traffic Demand

The changes in upstream and downstream flows between the capacity and non-capacity days were studied.

Upstream Main Carriageway Flow

The results for the upstream main carriageway flows are summarised in Table 31 and represented graphically in Figure 56.

Figure 56: Upstream Main Carriageway Flow (Capacity vs. Non-Capacity Days)

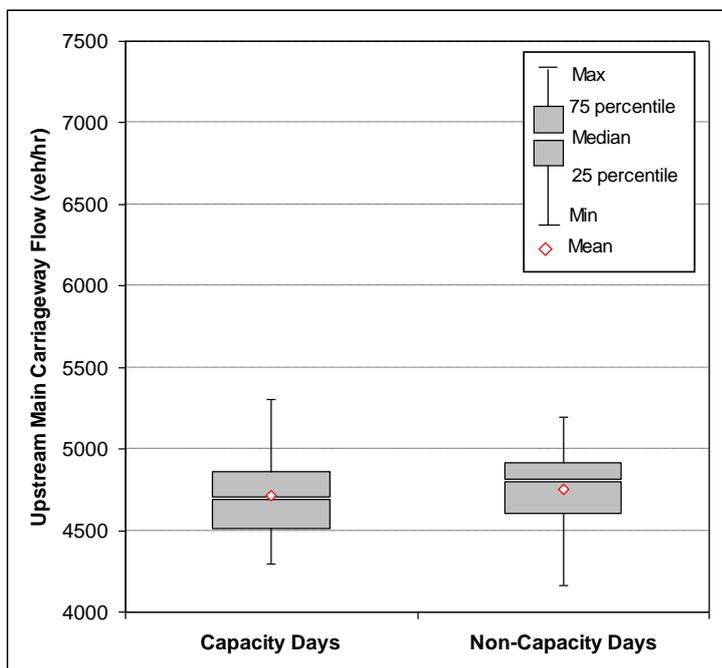


Table 31: Statistical Tests on Upstream Main Carriageway Flows

	Capacity Days	Non-Capacity Days
Mean Observed Flow (veh/hr)	4711	4753
Maximum Observed Flow (veh/hr)	5304	5196
Standard Deviation	274	279
F - test	0.95	
t - test	0.34	

Downstream Main Carriageway Flow

The results for the downstream main carriageway flows are summarised in Table 32 and represented graphically in Figure 57.

Figure 57: Downstream Main Carriageway Flow (Capacity vs. Non-Capacity Days)

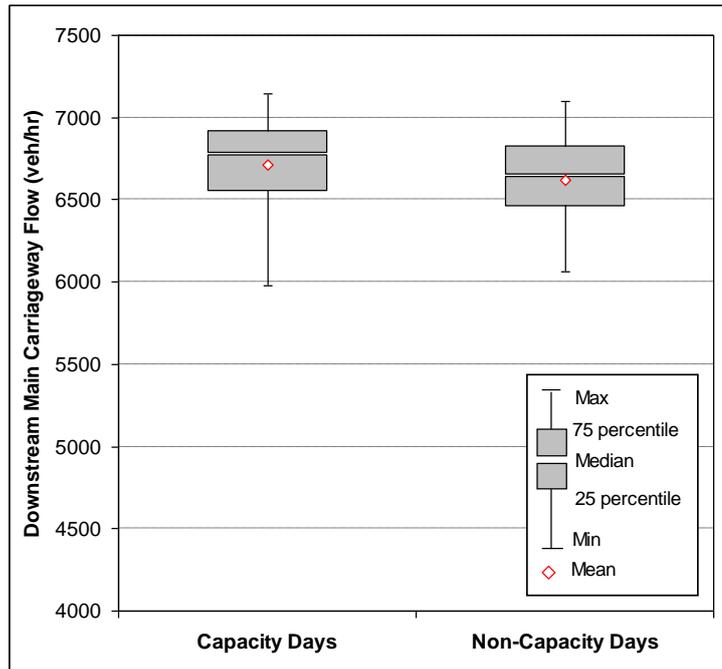


Table 32: Statistical Tests on Downstream Main Carriageway Flows

	Capacity Days	Non-Capacity Days
Mean Observed Flow (veh/hr)	6710	6617
Maximum Observed Flow (veh/hr)	7144	7100
Standard Deviation	341	301
F - test	0.63	
t - test	0.15	

On average, the maximum observed downstream flow during queue discharge was slightly higher on capacity days (6710 veh/hr) when compared to non-capacity days (6617 veh/hr). However, statistical testing has shown that there was no significant change in both upstream and downstream flows at the time when maximum flow throughput was observed for both cases.

This shows that the flow level of 6700 veh/hr is within the boundaries of Smart motorways capacity at M42 Junction 6 in the northbound direction. However, due to the small sample size it is not possible to accurately estimate the probability of observing flow-breakdown when flow levels are more than 6700 veh/hr. This is discussed in Section 6.

8.2.2. Traffic Composition

Figure 58: Percentage of HGVs (Capacity vs. Non-Capacity Days)

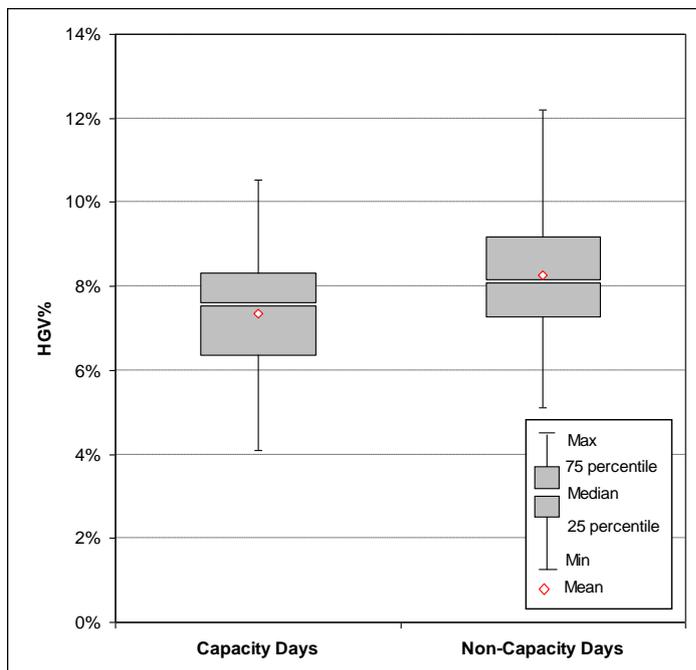


Table 33: Statistical Tests on HGV%

	Capacity Days	Non-Capacity Days
Mean Observed HGV%	7%	8%
Maximum Observed HGV%	11%	12%
Standard Deviation	2%	2%
F - test	0.62	
t - test	0.08	

To identify any difference in traffic composition between the capacity and non-capacity days, the HGV% was investigated. The analysis has shown that the average HGV% on capacity days and non-capacity days were 7% and 8% respectively. Statistical tests were undertaken to evaluate the difference in variability of the HGV% observed between the capacity and non-capacity days. Results have shown that the difference in HGV% was statistically insignificant and therefore cannot be regarded as sufficient to change the traffic characteristics between the two cases.

8.2.3. Hard Shoulder Utilisation

The change in hard shoulder utilisation downstream of the junction between the capacity and non-capacity days was also investigated. The analysis has shown that between 15:00 and 19:00 hours, the average hard shoulder utilisation on capacity days and non-capacity days was 13% and 10% respectively.

Figure 59: Hard Shoulder Utilisation % (Capacity vs. Non-Capacity Days)

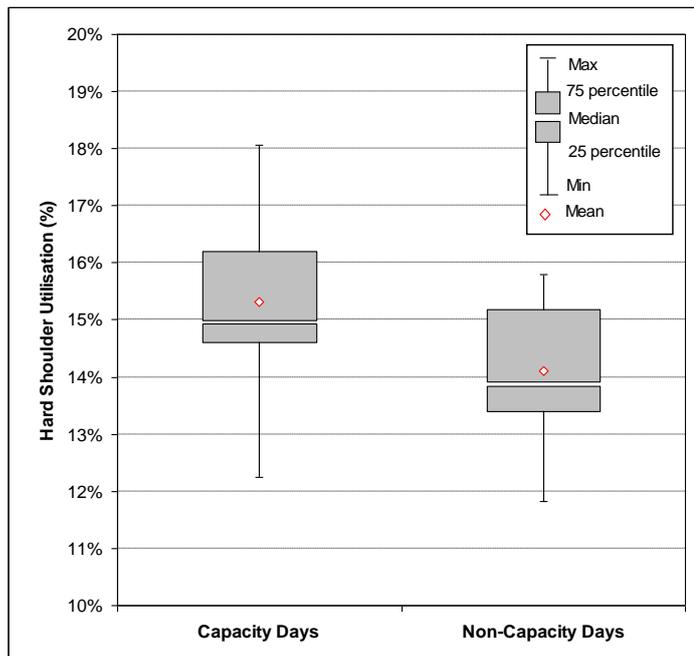


Table 34: Statistical Tests on HS Utilisation % (at the time of maximum flow)

	Capacity Days	Non-Capacity Days
Mean Observed HS Utilisation (%)	15%	14%
Max Observed HS Utilisation (%)	18%	16%
Standard Deviation	2%	1%
F - test	0.24	
t - test	0.01	

When looking into the hard shoulder utilisation at the time of maximum flow, results were found to be 15% on capacity days and 14% on non-capacity days.

Statistical tests were undertaken to evaluate the difference in the variability of HS utilisation observed between the capacity and non-capacity days, and results have shown that the differences were statistically significant. This implies that there is a general trend for the hard shoulder utilisation to increase in periods of congestion.

Although hard shoulder utilisation is slightly higher during capacity days, it was not as high as expected. It is likely that the layout of Junction 6 (i.e. tiger tail) may have contributed to such a result. Vehicles entering the motorway at the first merging section are forced to interact directly with the mainstream traffic which can create congestion. A different layout may result in higher usage of the hard shoulder and higher capacity.

It is also to be noted that the current Smart motorways operation operates on a lane gain/drop arrangement; therefore hard shoulder utilisation is somewhat limited.

8.2.4. Ramp Flow

Figure 60: Ramp Flow (Capacity vs. Non-Capacity Days)

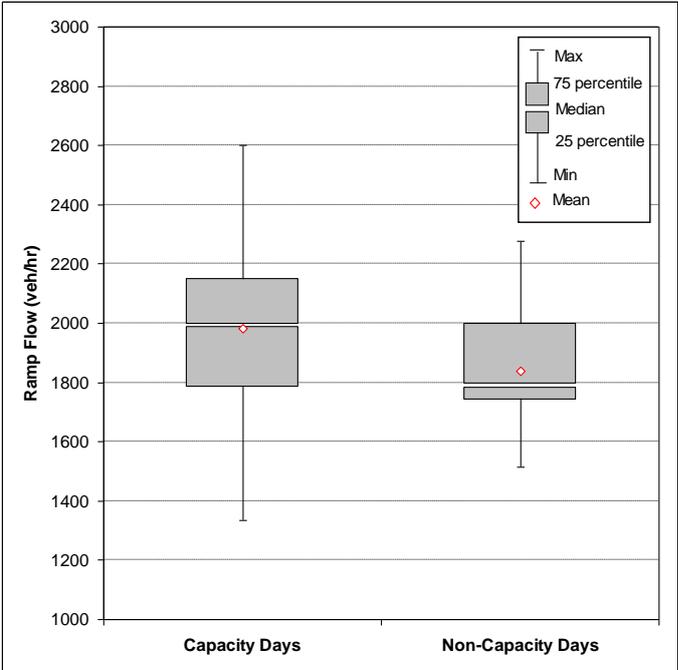


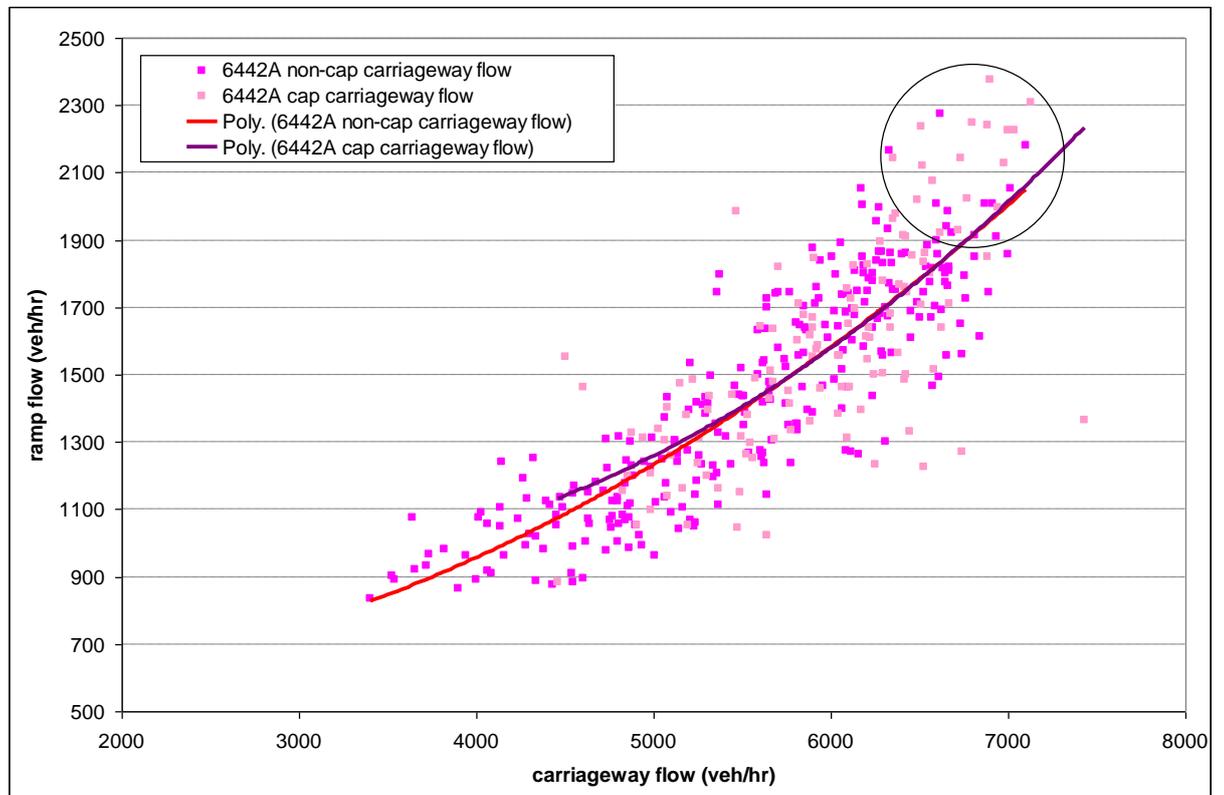
Table 35: Statistical Tests on Ramp Flows

	Capacity Days	Non-Capacity Days
Mean Observed Flow (veh/hr)	1981	1839
Maximum Observed Flow (veh/hr)	2600	2276
Standard Deviation	312	216
F - test	0.17	
t - test	0.03	

To identify changes in ramp flow during periods of high traffic demand, the differences in ramp flow between the capacity and non-capacity days were studied.

The average ramp flow observed on capacity days was 1981 veh/hr. Statistical tests were undertaken to evaluate the difference in the ramp flow and proportion of ramp flow observed between the capacity and non-capacity days, and results have shown that the differences were statistically significant. Therefore it could be concluded that ramp flow has a significant effect on motorway congestion at Junction 6 of the M42 motorway.

Figure 61: Ramp Flow vs. Downstream Main Carriageway Flow



The relationship between the ramp flow and downstream main carriageway flow are as shown above in Figure 61. From this figure it can be noted that there is a greater cluster of points on capacity days associated with higher ramp flows and main carriageway flows when compared to non-capacity days.

8.3. Discussion

8.3.1. Ramp Metering

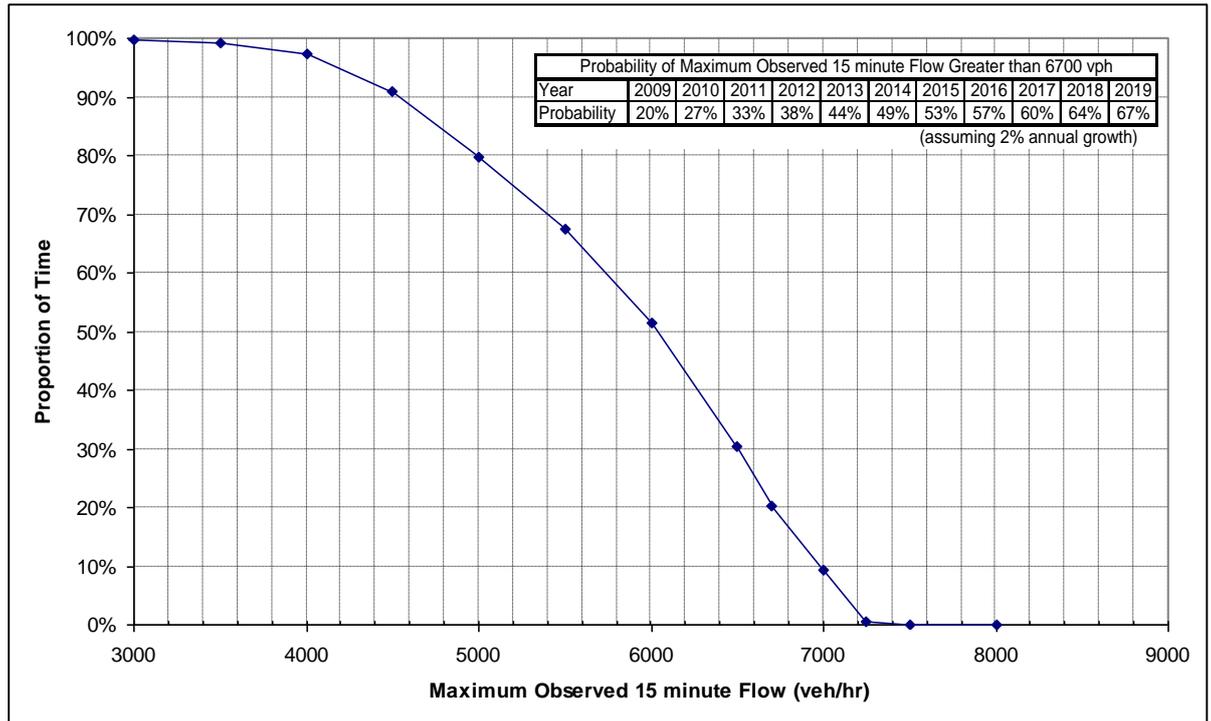
It should be noted that ramp metering has been operational along the M42 Smart motorways section since October 2008. Through this study, it was identified that ramp metering was in operation on 8 out of 9 days of the capacity days under the operation of HSR60. Ramp metering was not in operation on the non-capacity days. The assessment of ramp metering has indicated a benefit of ramp metering on downstream flow, although this was mostly linked to the operation of HSR at 60 mph. This result should not affect this study as both HSR60 and HSR50 were considered in a balanced way.

8.3.2. Future Traffic Growth

In Section 5.1, it was identified that on average, the maximum observed flow during queue discharge was 6710 veh/hr. This value can be considered as an indicator at which traffic travelling through the M42 Junction 6 may reach capacity under Smart motorways operation.

The proportion of time at which the maximum observed 15 minute flow between the periods of June 2008 – May 2009 exceeded specific flow levels on the M42 [J6-J7] northbound link was investigated and presented in Figure 62. This shows that traffic demand has exceeded 6700 veh/hr on approximately 20% of the days (i.e. 74 days).

Figure 62: Proportion of Time when Max 15 min Flow is Greater than X



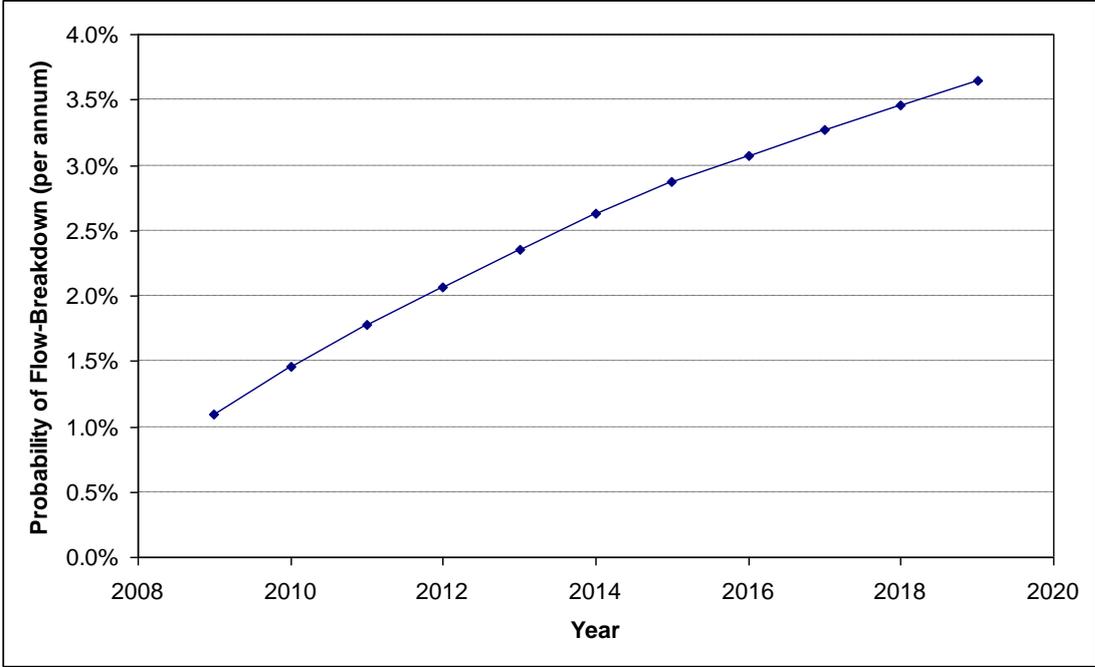
Within the ATM 12 month report, it was stated that the observed increase in traffic demand along the M42 Smart motorways section between 2002 and 2007 was 6% and 9% in the northbound and southbound directions respectively. This figure was similar to the reported 7.9% national growth in traffic, which approximates to a growth of 1.2 – 1.8% per annum.

Assuming a 2% annual traffic growth (as a ‘worse case’ scenario for exploring the life-span of the M42 Smart motorways section), the probability of observed traffic flows exceeding 6700 veh/hr was evaluated and summarised in a table which can be found in Figure 62. Based on these figures, it has been estimated that the probability of traffic demand exceeding 6700 veh/hr will be 50% by the year 2015.

It should be noted that although it has been estimated that 50% of the days will exceed 6700 veh/hr in 2015, not all of these days will suffer from congestion. Therefore it is important to estimate the probability of breakdown when flow exceeds 6700 veh/hr.

The data shows that of the 74 days where maximum 15 minute flow exceeded 6700 veh/hr, flow-breakdown was observed on 4 days where HSR was also in operation. This gives a 5.5% probability of flow-breakdown occurring at flows over 6700 veh/hr.

Figure 63: Probability of Flow-Breakdown (per annum)



Based on the findings from Figure 62, the probability of flow-breakdown occurrence per annum has been estimated and is summarised in Figure 63. This has been evaluated based on the number of days exceeding 6700 veh/hr per year, and applying the 5.5% probability of flow-breakdown occurring at flows over 6700 veh/hr. This shows that the probability of flow-breakdown occurring at this junction is approximately 3.6% per annum by the year 2019.

Due to the small data set, the figures quoted within this section are only indicative and cannot be supported by statistical analysis. The probability was evaluated in a simplified manner without considering the influence of changing ramp demand and seasonality. However, the results can be used as an indication to aid the purpose of this study.

CHAPTER 9

Lane Utilisation and Traffic Capacity

9.1. Introduction

As discussed throughout this research, one of the aims of smart motorways is to improve the distribution of traffic between lanes. Lane utilisation of an individual lane can be represented as follows:

$$\text{Lane utilisation (\%)} = \frac{\text{Flow}_i}{\text{Total flow across all lanes}} * 100 \quad \text{where } i = \text{lane considered}$$

It is regarded that as traffic demand approaches close to capacity, lane utilisation across all lanes become more uniform; i.e. under ideal conditions, optimal utilisation of a motorway occurs when the traffic utilisation is equal across the running lanes, which is evaluated as follows:

$$\text{Optimal utilisation(\%)} = \frac{100}{\text{Number of operating lanes}}$$

Using the equation above, the optimal utilisation of a motorway during smart motorway operation is evaluated as 25% (as there are 4 running lanes). However, the findings from CHAPTER 5 and CHAPTER 6 showed that average utilisation of the hard shoulder was on average 12%, indicating that the hard shoulder is not fully utilised.

In this chapter, lane utilisation during smart motorway operation was examined to better understand the overall performance of this operational regime.

9.2. Methodology

9.2.1. Dataset and source

Similar to the capacity study presented in CHAPTER 8, this study has focused on congestion conditions and when HSR was in operation. The analysis was carried out using Individual Vehicle Data, to understand the observations made in CHAPTER 6 (Through Junction Running) and CHAPTER 8 (Capacity Study) further, as this dataset provides detailed vehicle composition information on a lane-by-lane basis.

As mentioned in CHAPTER 4, IVD is in essence raw MIDAS data and records each vehicle passing over a MIDAS loop as an individual record. The data therefore had to be processed to aggregate the data into a format required for carrying out a multivariate analysis with SPSS. It was again important to ensure that no incidents were observed at the time of congestion upstream and/or downstream of the site.

Table 36: List of IVD Loops Used for Capacity Analysis

Loop Location (Link)	MIDAS Reference
M42 J3A-J4 NB	M42/6310A
M42 J4-J3A SB	M42/6312B
M42-J4-J5 NB	M42/6350A
M42 J5-J4 SB	M42/6350B
M42 J5-J6 NB	M42/6492A
M42 J6-J5 SB	M42/6494B
M42 J6-J7 NB	M42/6446A
M42 J7-J6SB	M42/6446B

IVD data from September 2006 and April 2009 was used as a part of the analysis carried out within this chapter.

9.2.2. Analysis approach

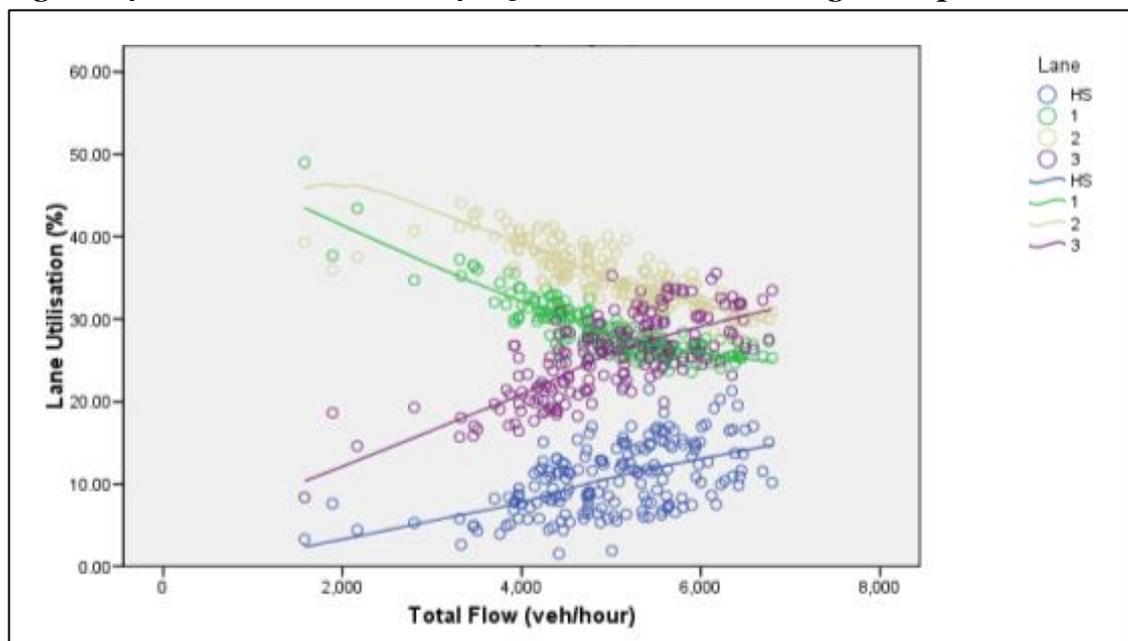
The analysis firstly examined the relationship between lane utilisation and traffic flow under smart motorway conditions. As mentioned earlier, it was identified that hard shoulder utilisation was potentially not fully utilised to maximise road capacity.

Once the relationship between hard shoulder utilisation and other traffic parameters were better understood, a multivariate analysis was carried out to derive a model which described motorway capacity under smart motorway conditions. The factors considered within this particular analysis are outlined later in Section 9.5.1.

9.3. Lane Utilisation

Figure 64 shows the lane utilisation on the M42 J5-J6 section during HSR operations. The figure shows that when traffic flow is still low (i.e. during build-up), the majority of traffic are on Lanes 1 and 2.

Figure 64: Lane utilisation on M42 J5-J6 Northbound during HSR operations



The figure also shows that traffic flows on the hard shoulder increases, and the lane utilisation on Lanes 1, 2 and 3 become very similar. The results for the other links were similar and are presented in

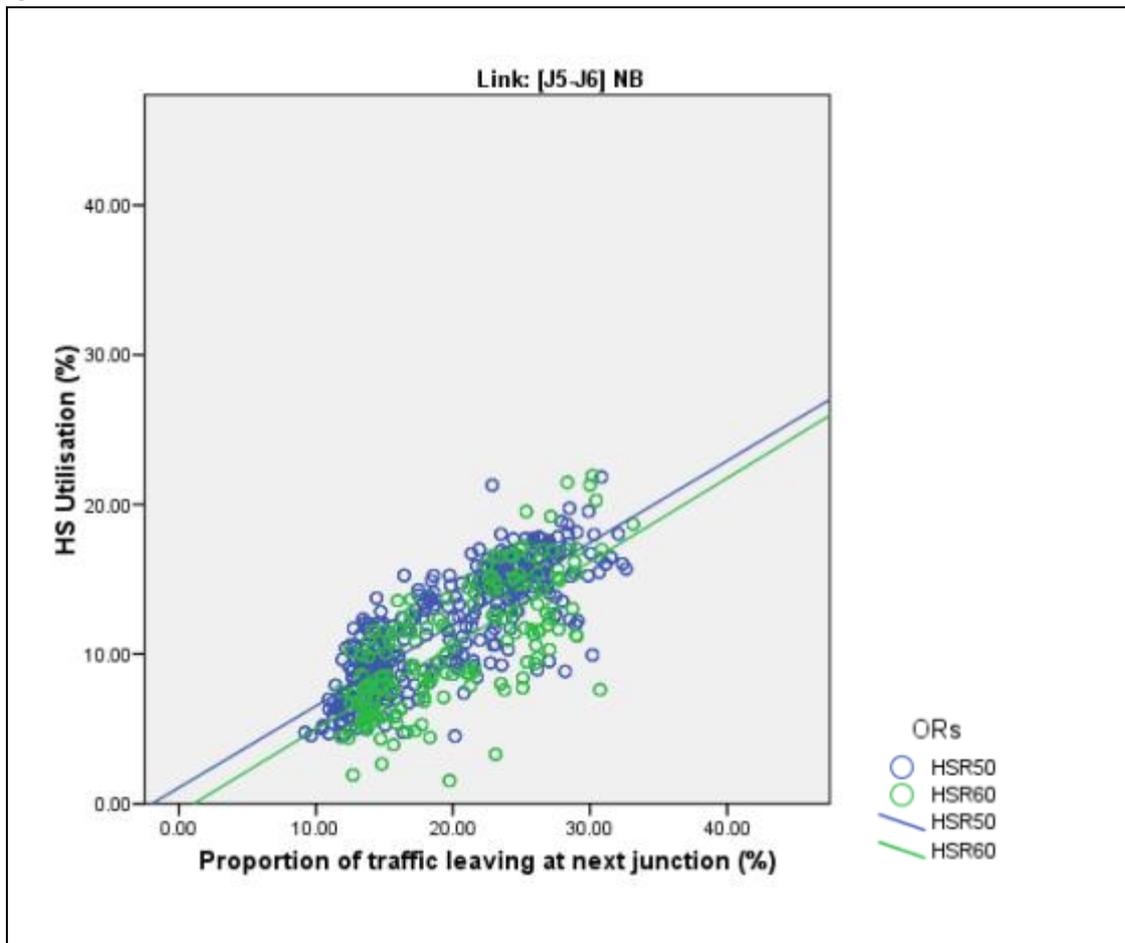
Appendix D: Lane Utilisation during HSR operations.

As discussed in Section 6.3, HSR sites without TJR is in a lane gain/drop arrangement and therefore identified that this arrangement may be limiting the full potential of HSR. The relationship between hard shoulder utilisation and proportion of traffic leaving at the next junction was examined to understand this observation further.

9.3.1. Hard shoulder utilisation and proportion of traffic leaving at next junction

Figure 65 shows an example of the relationship between hard shoulder utilisation and traffic leaving at the next junction during HSR operations. The graph shows that there is a linear relationship between the two, suggesting that the current lane-gain/drop arrangement could potentially be limiting the use of all running lanes during periods of congestion.

Figure 65: Hard shoulder utilisation vs proportion of traffic leaving at next junction



The results for the other links are presented in

Appendix E: Hard shoulder utilisation vs proportion of traffic leaving at next junction. The profiles and observed relationships were generally similar, with the exception of M42 J4-J3A Southbound.

The coefficients describing the linear relationship have been extracted and are presented in Table 37.

Table 37: Coefficients for hard shoulder utilisation

Link	OR	Coefficients		r ²
		A	B	
J3A – J4 NB	HSR50	0.80	-0.21	0.56
	HSR60	0.88	-2.57	0.72
J4 – J3A SB	HSR50	-0.21	19.25	0.06
	HSR60	-0.23	19.05	0.09
J4 – J5 NB	HSR50	0.50	4.87	0.20
	HSR60	0.67	1.44	0.39
J5 – J4 SB	HSR50	0.71	0.04	0.85
	HSR60	0.69	-0.84	0.87
J5 – J6 NB	HSR50	0.55	1.01	0.67
	HSR60	0.56	-0.61	0.53
J6 – J5 SB	HSR50	0.57	2.54	0.39
	HSR60	IVD not available over study period		
J7 –J6 SB	HSR50	0.90	-3.19	0.80
	HSR60	0.90	-5.02	0.73

Where HS Utilisation = A* (proportion of traffic leaving at next junction) + B

All links show that the two parameters considered have a positive relationship, with the exception of the J4-J3A southbound link. This is largely attributed to the road lay-out of this section of road, as this link splits into two sets of two lanes and the end of the section; one leading to the M40 westbound and the other following the M42 towards M5 J4A.

9.4. Distribution of speed

Before carrying out the detailed analysis, the distribution of speed during smart motorway operations for each lane and signal setting was examined to identify whether traffic conditions on adjacent lanes had an impact on one another and subsequently to decide the variables to include within the analysis. The HCM reports that that distribution of vehicle speeds was unique for each lane and vehicle class, therefore it was important to understand how the introduction of VMSL had impacted this parameter as HSR aims to increase the observed motorway capacity by harmonising speed and thereby preventing the occurrence of flow-breakdown. The results are presented in Figure 66 (for signal = 60 mph), Figure 67 (signal = 50 mph) and Figure 68 (signal = 40 mph).

Figure 66: Distribution of speed by lane (Signal = 60 mph)

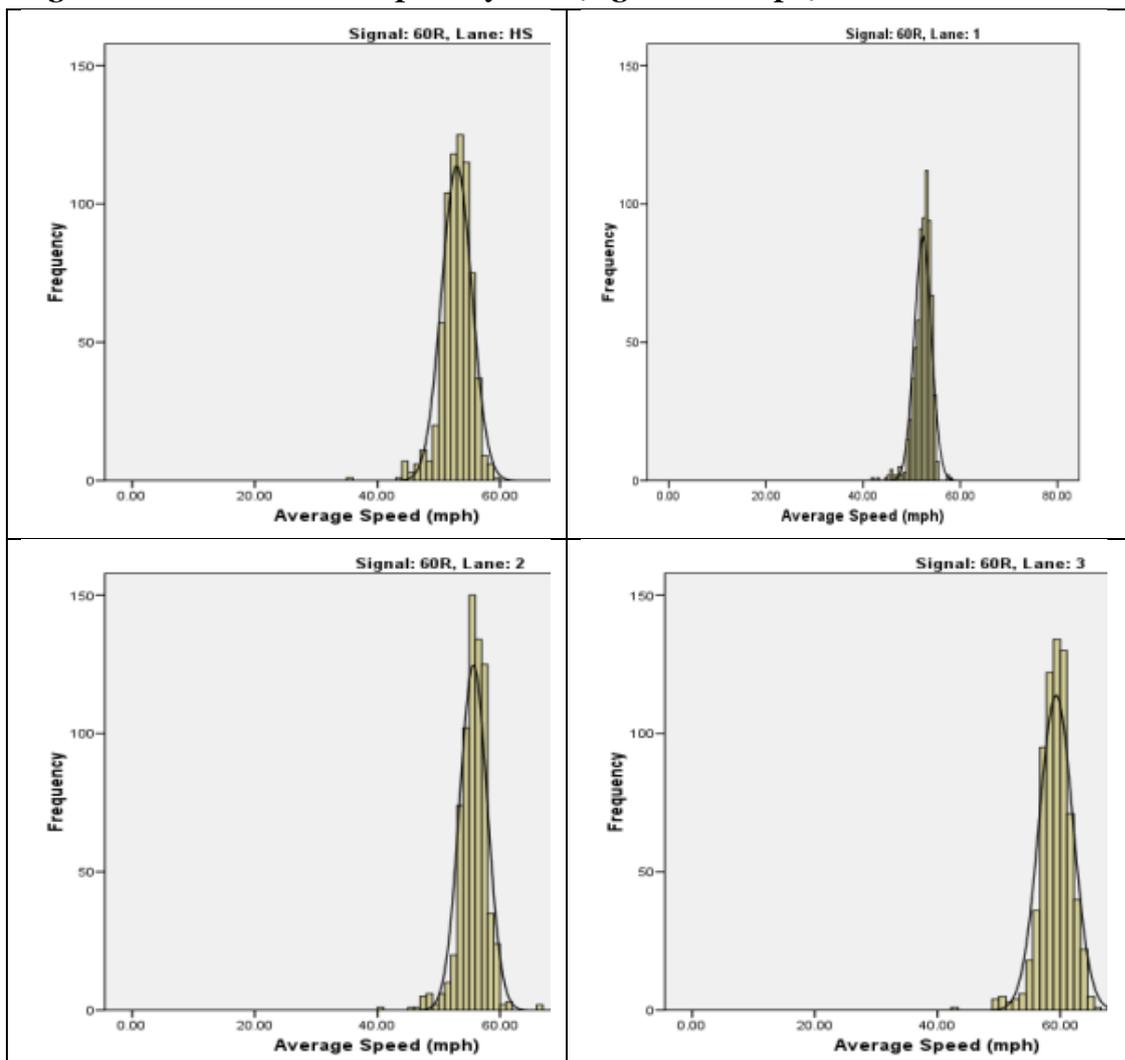


Figure 67: Distribution of speed by lane (Signal = 50 mph)

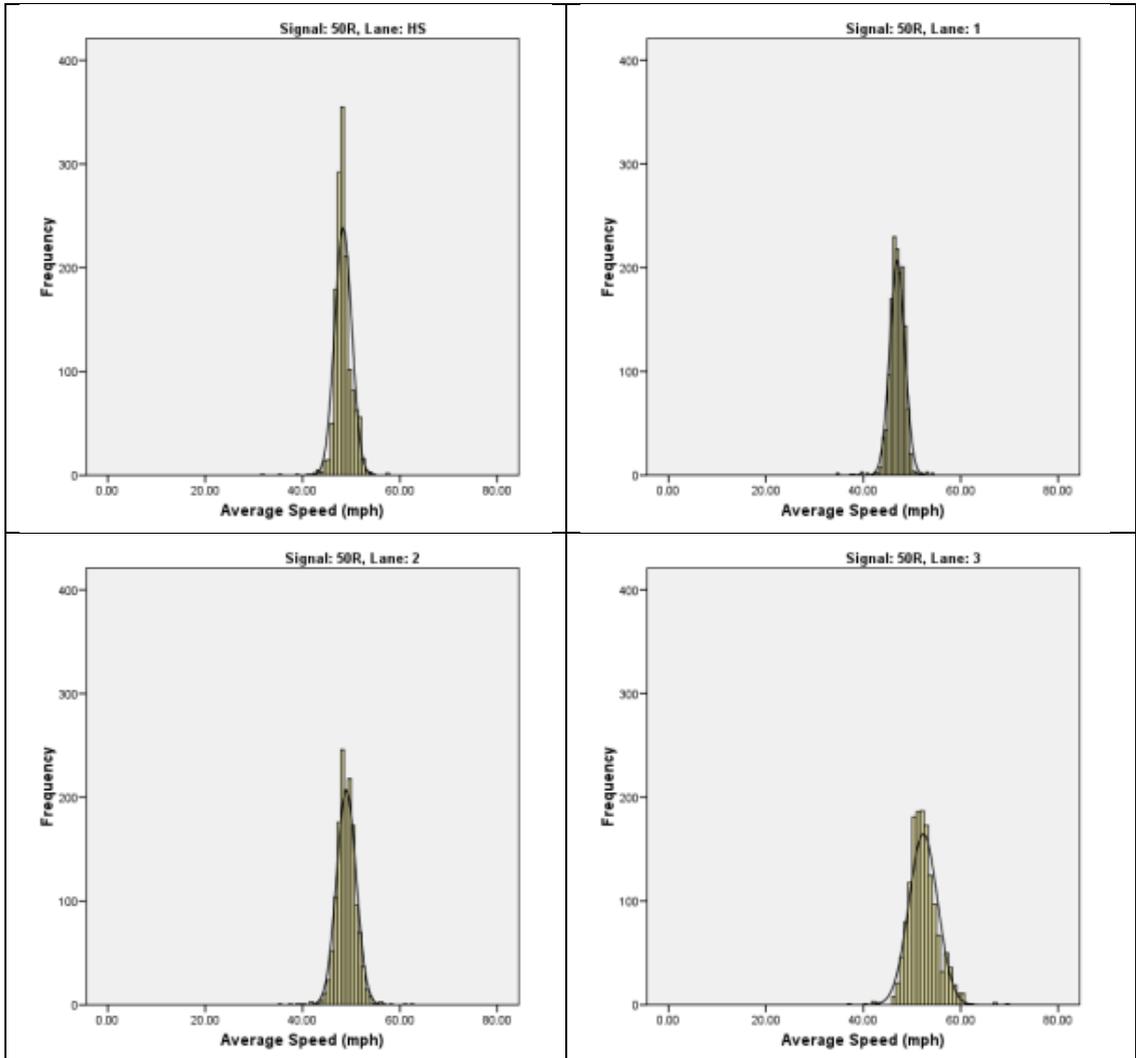
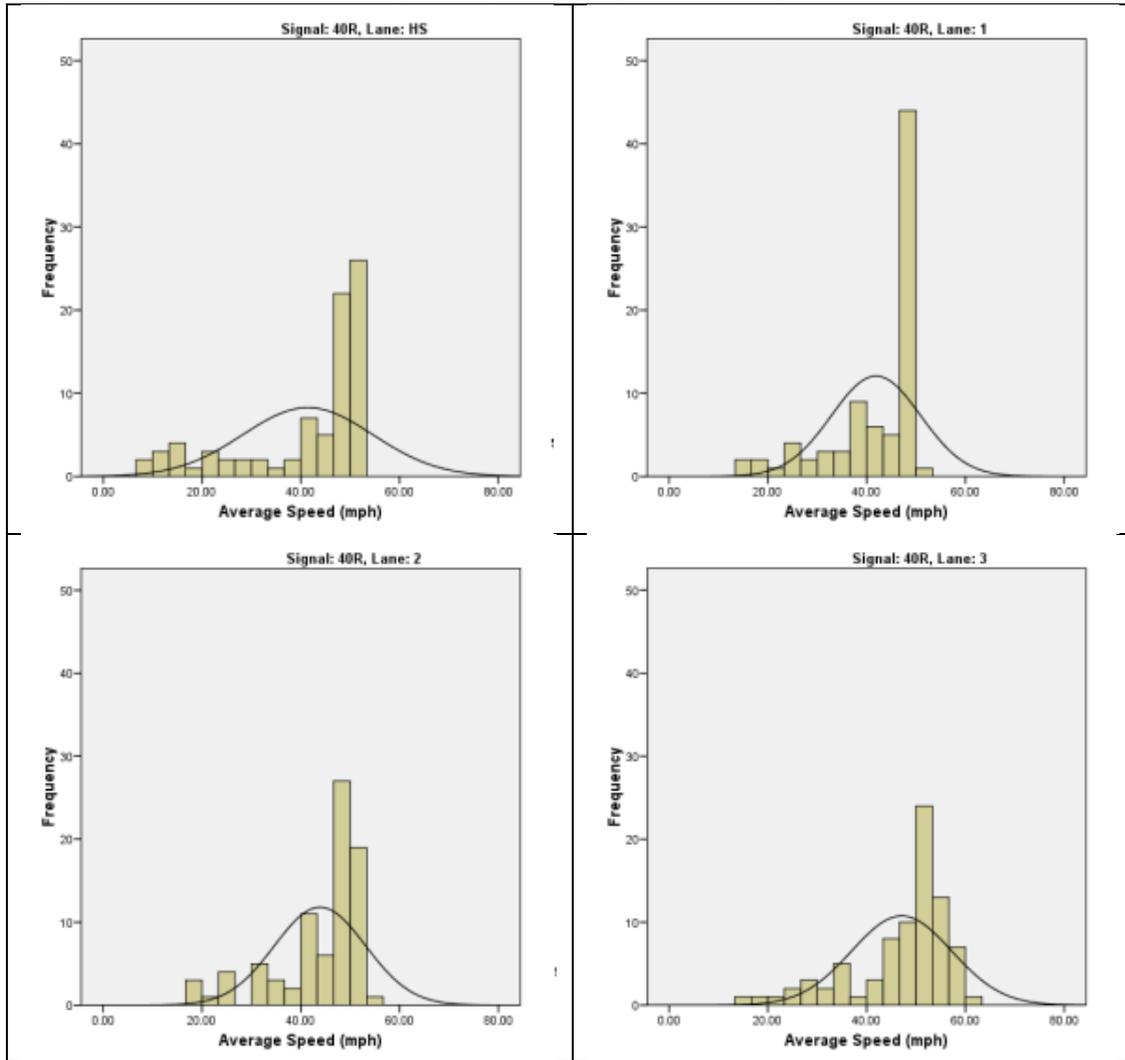


Figure 68: Distribution of speed by lane (Signal = 40 mph)



The distribution of speed by lane at the 40 mph speed limit does not show a normal distribution such as that shown for the 50 mph and 60 mph speed limits. The mean and standard deviations of the average speeds presented in the figures above have been summarised in Table 38.

Table 38: Means and standard deviations of average speed (by lane and signal)

	Hard Shoulder		Lane 1		Lane 2		Lane 3	
	μ	σ	μ	σ	μ	σ	μ	σ
Signal = 60 mph	52.95	2.46	52.29	1.76	55.67	2.24	59.31	2.73
Signal =50 mph	48.36	1.74	46.97	1.56	48.99	2.01	52.32	2.94
Signal = 40 mph	41.41	13.18	41.90	9.03	43.89	9.24	47.09	10.14

The results support the findings presented in Section 6.5.2 where the speed distribution between lanes was presented and demonstrate that motorists respond to the displayed speed limits and change their speeds during HSR operations. Speeds on the hard shoulder and Lane 1 were comparable for the 40 mph and 60 mph limit, and the speeds between the hard shoulder, Lane 1 and Lane 2 were comparable for the 50 mph limit.

In addition, it can be noted that for the 50 mph and 60 mph speed limits, the standard deviations were smaller than compared to when the 40 mph limit was displayed. This is due to the fact that the 40 mph speed limit is generally set during periods when flow is highly unstable and is about to (or already) breakdown.

9.4.1. Speed difference between adjacent lanes

As discussed in the earlier sections, smart motorways aim to increase the observed motorway capacity by harmonising speed. Prior to the deployment of HSR60, there have been concerns that the introduction of an increased speed limit (i.e. 60 mph signal setting) may lead to a greater variation in average traffic speeds across lanes. This was due to HGVs generally being limited to a maximum speed of 56 mph; therefore this potential increase in speed variation may result to a reduced capacity

The results presented in Table 38 shows that the distribution of speed on the hard shoulder was greater on the hard shoulder, lane 1 and 2 during the 60 mph speed limit compared to the 50 mph limit. Therefore a more detailed analysis was carried out to understand this observation further, by comparing the speed difference between lanes with similar speeds on Lane 1. The results are presented in Figure 69.

Figure 69: Speed difference between adjacent lanes vs. speed on lane 1

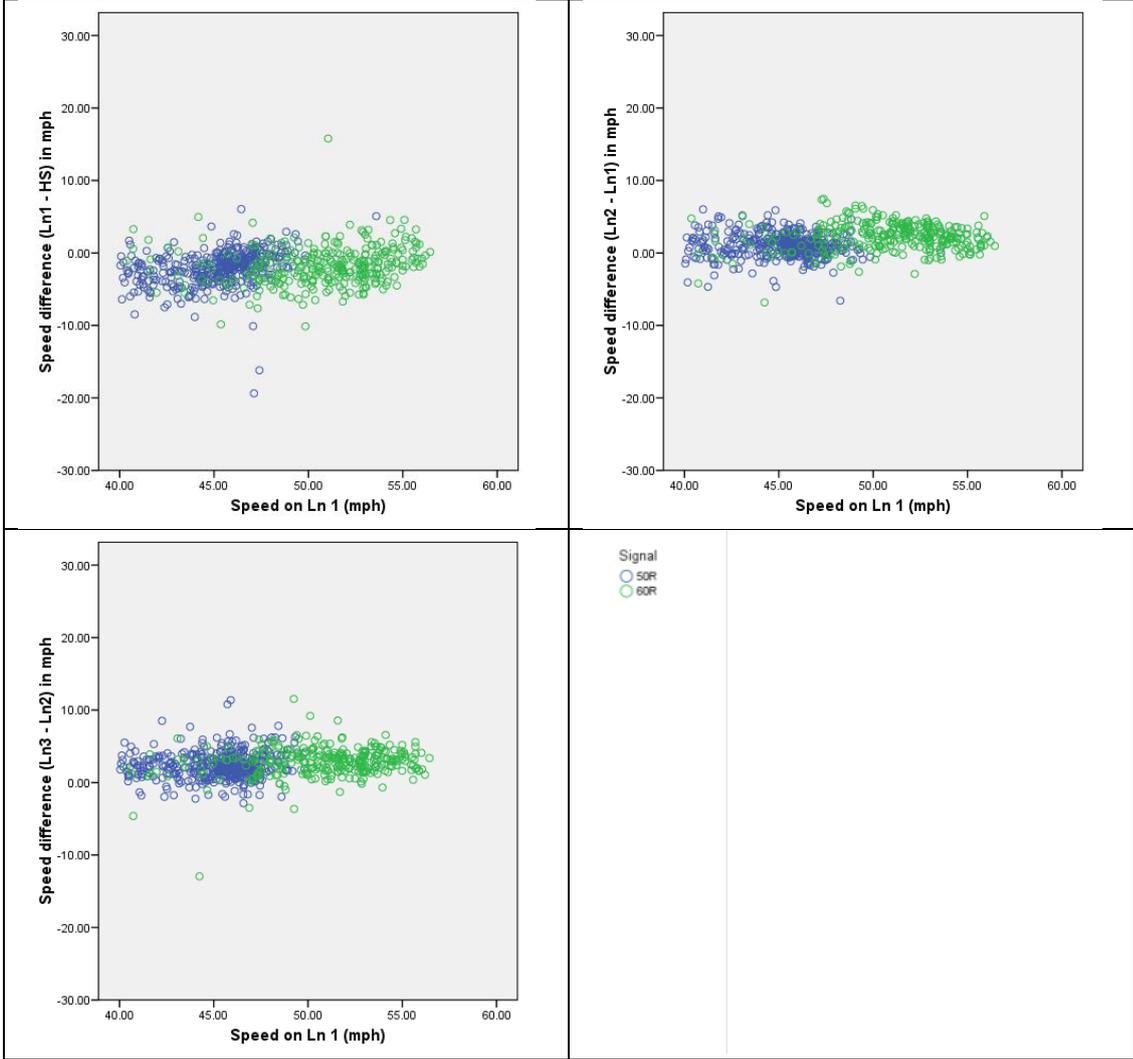
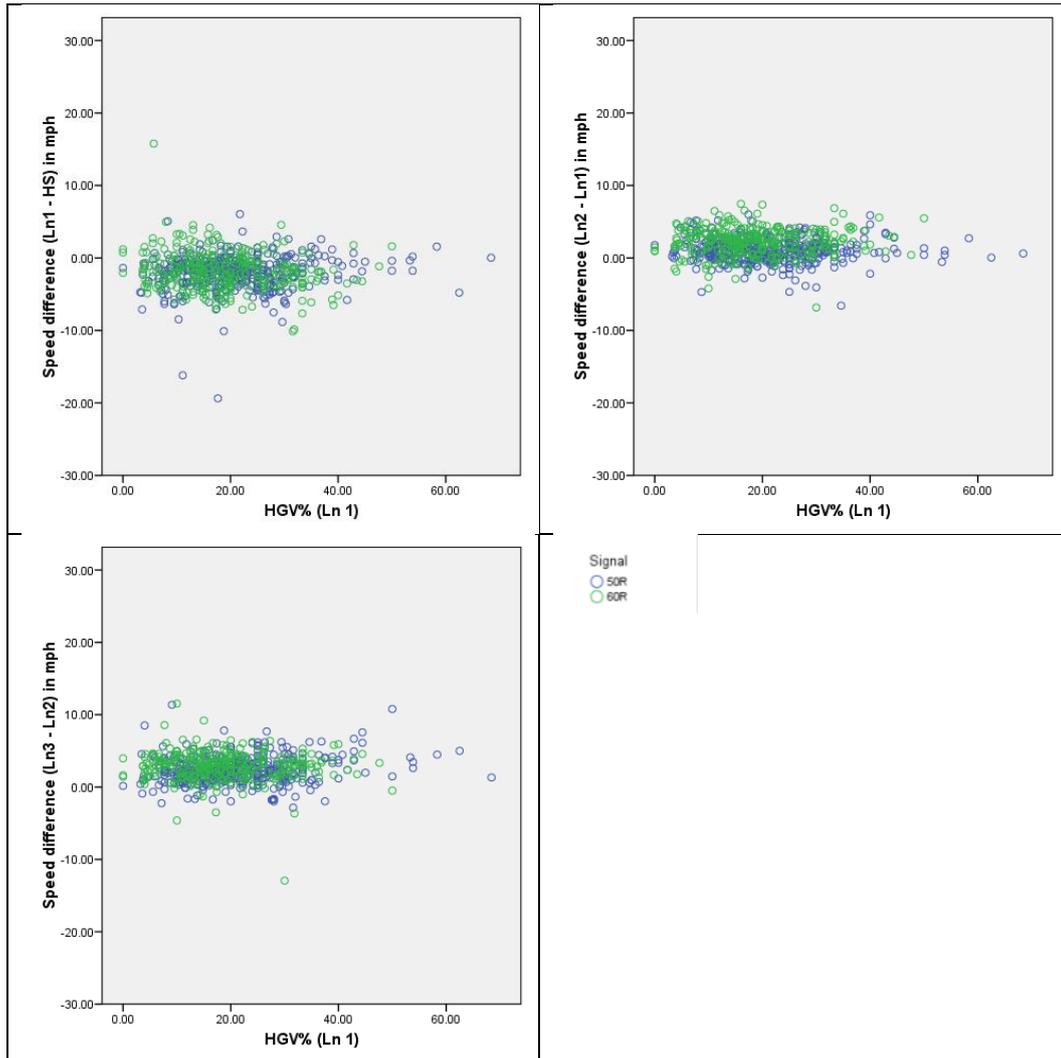


Figure 69 shows that the speed difference between adjacent lanes did not vary with speeds on Lane 1, regardless of signal settings introduced. This was further examined by looking at whether the number of HGVs on the hard shoulder and lane 1 had an effect on the speed differential between lanes. The results are presented in Figure 70 and again show that the proportion of HGVs did not have an impact on the speed difference between adjacent lanes for both signal settings.

Figure 70: Speed difference between adjacent lanes vs. HGV% on lane 1



9.5. Multivariate analysis

9.5.1. *Inputs to the analysis*

Based on the literature review and analysis carried out to this point, the following parameters were considered to evaluate the motorway capacity during smart motorway operations:

Table 39: Parameters considered in the multivariate analysis

Parameter	Reason
Signal setting	As identified in Section 9.4, driver behaviour is directly influenced by the displayed signal settings on a smart motorway scheme.
Lane utilisation	As discussed, it is regarded that as traffic demand approaches close to capacity, lane utilisation across all lanes becomes more uniform.
Proportion of traffic leaving at the next junction (%)	The proportion of traffic has a direct correlation with lane utilisation (for most sites), but may vary according to site and traffic conditions
Average speed by lane (mph)	Smart motorways aims to improve traffic conditions and reduce the onset of flow breakdown by 'harmonising' the vehicle speeds across the individual lanes.
HGV (count and/or percentage)	The statistical tests carried out in Section 8.2 showed that the difference in HGVs and HGV% were statistically insignificant and therefore cannot be regarded as sufficient to change the traffic characteristics between congested and non-congested conditions. The similar was also suggested by the outputs presented within Section 9.4, however, this parameter was included as a part of the analysis as past research work have identified traffic composition as a contributing factor to limit motorway capacity.

9.5.2. Outputs from multivariate analysis

The various analysis tools within SPSS was used to complete this section of work. Table 40 presents the variables which have been defined from the multivariate analysis.

Table 40: Coefficients of regression at varying signal settings

Parameter	Signal Setting		
	60 mph	50 mph	40 mph
Intercept	12159.12	13720.32	13264.28
Lane Utilisation (HS)	-18.0392	-62.68	-86.0716
Lane Utilisation (Ln 1)	-75.6272	-74.69	-89.1754
Lane Utilisation (Ln 2)	-140.543	-221.3	-233.876
Speed_HS	63.42254	40.506	36.92667
Speed_Ln1	-58.0001	33.863	34.1833
Speed_Ln2	--	-30.53	--
% of offslip flow	-24.4373	-19.01	-12.124
r ²	0.698	0.699	0.815

The process confirmed that HGVs did not have an influence on motorway capacity during HSR operations. This is due to the traffic being controlled by the VMSL displayed, thereby during congestion, all vehicles are essentially in car-following mode and achieving speed harmonisation across all lanes. The r² for all signal settings considered were greater than 0.5, which is considered to be strong in statistical terms, providing a good estimate on motorway capacity during smart motorway operations.

The road capacity during smart motorway operations was estimated using the coefficients derived and presented in Table 40. As the model relies on a number of factors, varying factors, the following assumptions have been made for the purpose of discussion within this section:

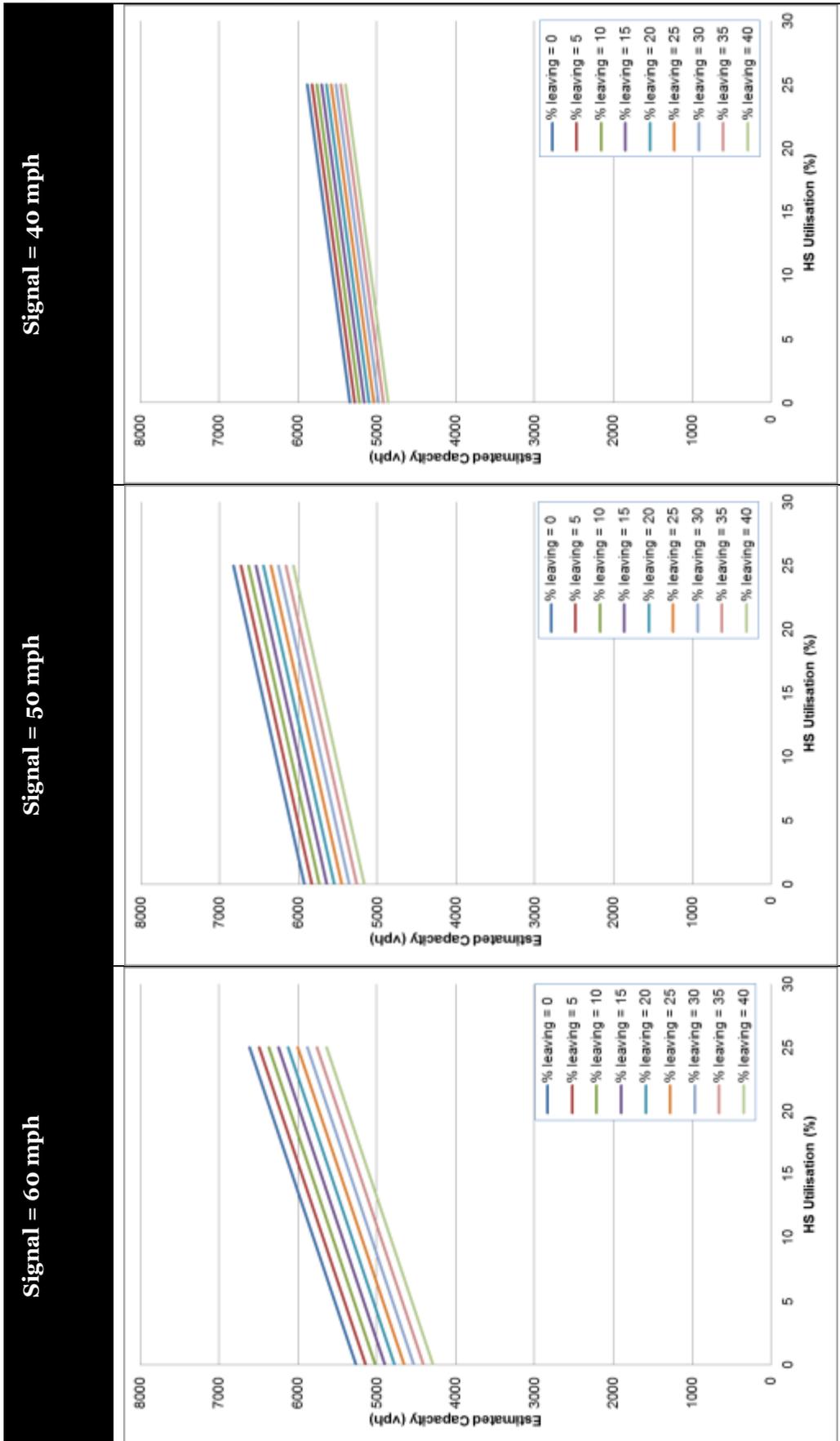
- Traffic speeds on each lane were as presented in Table 38.
- Lane utilisation on Lanes 1, 2 and 3 were homogenous, i.e.:

$$\text{Lane utilisation on Lanes 1, 2 and 3 (\%)} = 100 - \frac{HS \text{ Lane utilisation}}{3}$$

- Graph to be drawn for varying proportion of traffic leaving at the next junction

The results are presented graphically in Figure 71.

Figure 71: Estimated capacity levels during smart motorway conditions



The results presented in this section have been based on 15 minute data as discussed in CHAPTER 4. Data with lower time intervals (i.e. 1 min and 5 min) were also tested but unable to generate a reliable result due to the high variance (i.e. scatter) within the dataset.

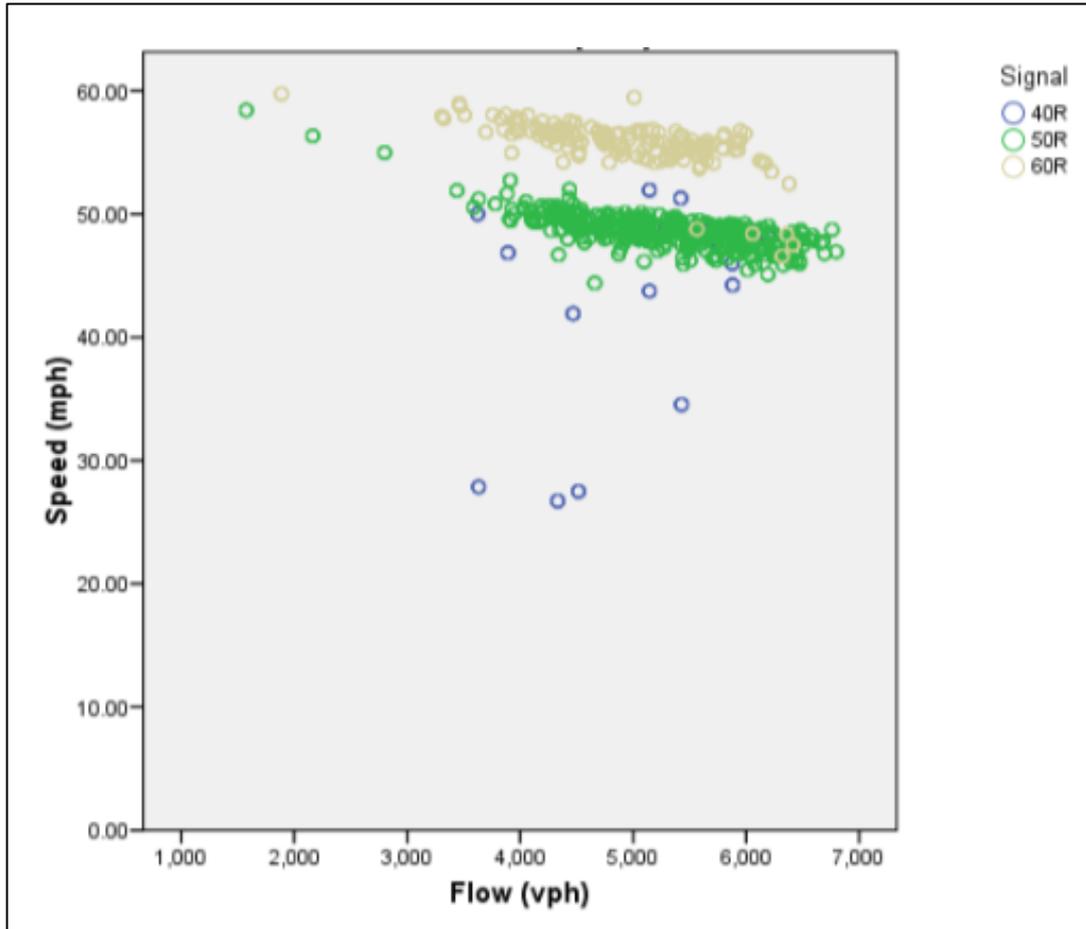
For all three models, the lane utilisation on lanes 1 and 2 were the principle components contributing to the estimated capacity. The figures in the example shown also indicates that for the same level of hard shoulder utilisation, an increase in proportion of traffic leaving at the next junction would result in a reduction in motorway capacity as expected; thus highlighting the importance of optimising lane utilisation on the motorway.

Two key observations were also made within the graphs:

1. The estimated maximum capacity for the 60 mph and 50 mph speed limits were similar, but higher in the 50 mph speed limit
2. The variance in estimated capacity by proportion of traffic leaving at the next junction appeared to become less (i.e. narrower bands) as the speed limits reduced.

A sample speed/flow graph was referred to help understand the observation above.

Figure 72: Sample speed/flow graph



As seen in the diagram, as traffic flow grows the average traffic speed reduces, therefore VMSL is being introduced to smooth the traffic and maintain the stable traffic conditions. During the study period, the 50 mph and 60 mph signal were predominantly set over periods of congestion and the plot illustrates the transition between the various signal settings at a given flow and speed. The diagram explains and supports the finding in Figure 71 where higher capacity were estimated at 50 mph, and demonstrates that the smooth transition in speed is enabling traffic to gain additional throughput, even when reducing the speed limits on the road.

9.6. Summary

This chapter examined lane utilisation during manage motorway operations and its effect to the overall performance of this operational regime. It is regarded that as traffic demand approaches close to capacity, lane utilisation across all lanes become more uniform; i.e. under ideal conditions, optimal utilisation of a motorway occurs when the traffic utilisation is equal across all lanes.

Lane Utilisation

It was found that:

- When traffic flow is still low (i.e. during build-up), the majority of traffic are on Lanes 1 and 2.
- As traffic flows on the hard shoulder increases, and the lane utilisation on Lanes 1, 2 and 3 become very similar.
- Hard shoulder utilisation and proportion of traffic leaving at next junction are directly proportional to one another

Distribution of speed

It was important to understand how the introduction of VMSL had impacted this parameter as HSR aims to increase the observed motorway capacity by harmonising speed and thereby preventing the occurrence of flow-breakdown. The data confirmed that:

- motorists respond to the displayed speed limits and change their speeds during HSR operations.
- Speeds on the hard shoulder and Lane 1 were comparable for the 40 mph and 60 mph limit, and the speeds between the hard shoulder, Lane 1 and Lane 2 were comparable for the 50 mph limit.
- Standard deviation of average speeds for the 50 mph and 60 mph speed limits were smaller than compared to when the 40 mph limit

Multivariate analysis

A multivariate analysis was carried out to establish a model which described motorway capacity during smart motorway operations using various traffic parameters. A model was developed which used the following parameters:

- Lane Utilisation (HS)
- Lane Utilisation (Ln 1)
- Lane Utilisation (Ln 2)
- Speed_HS
- Speed_Ln1
- Speed_Ln2
- Proportion (%) of offslip flow

The r^2 for all signal settings considered were greater than 0.5, which is considered to be strong in statistical terms, providing a good estimate on motorway capacity during smart motorway operations.

CHAPTER 10

Conclusions and Recommendations

10.1. Summary

With smart motorways being introduced to wider areas of Highways England's road network, it has become more important to understand the limitations of this application to inform the decision on future site selection and its life-span. Therefore there is a need to gain an understanding of the limitations within smart motorways operations to support Highways England, highways designers and other key stakeholders to when making decisions on traffic management strategies to be implemented. This research used traffic data collected from the MIDAS loop detectors to examine the various traffic parameters during smart motorway operations.

Publications such as the Highways Capacity Manual (HCM) and Design Manual for Roads and Bridges (DMRB) provide capacity estimates and descriptions for Levels of Service, however, there is no similar guidance for smart motorway operations based on empirical analysis and research reflecting English road conditions to date. The data considered MIDAS data on the M42 smart motorway section from the period between September 2006 and March 2012, and IVD data from September 2006 and April 2009; therefore is considered to be of a large data set of this type of motorway operations.

The findings from this research have supported Highways England with the development of Interim Advice Notes and Best Practice notes relating to smart motorway operations, and selection of smart motorway sites and operational regime(s) to be implemented.

10.1.1. Understanding capacity

A review of the evolution of smart motorways and examining the performance of HSR schemes outside of the UK has demonstrated that this type of application has been effective in addressing congestion, providing additional road capacity and giving improvements in journey times (associated with improvements in traffic speeds) in an effective and efficient matter. There are a number of difference factors which affect motorway capacity, those which are common to all motorways and those which are unique to smart motorways:

Factors which affect motorway capacity

- Physical Features of the Carriageway
- Traffic Conditions
- Ambient Road Conditions
- Driver Behaviour

Factors Unique to Smart motorways

- Use of the hard shoulder as a running lane (HSR)
- Variable Mandatory Speed Limits (VMSL)
- Emergency Refuge Areas (ERAs)

The effect of VMSL to traffic parameters and the use of the hard shoulder as an additional running lane have been examined to better understand the performance of smart motorways throughout this thesis.

10.1.2. Probability of flow-breakdown

A capacity study on the M42 Junction 6 northbound was carried out to understand the traffic conditions between capacity and non-capacity days, where these days were defined by applying a selection criteria based on demand and HSR operation. Results have shown that:

- There was no statistically significant difference in traffic throughput and composition between capacity days and non-capacity days.
- There was a statistically significant increase in hard shoulder utilisation of 1% between the capacity and non-capacity days (i.e. congestion encourages more use of the hard shoulder).
- There was a statistically significant increase in ramp demand (i.e. merging traffic) on capacity days, which was identified as a potential contributing factor of flow-breakdown occurrence.
- On average, the maximum flow observed at queue discharge capacity days (i.e. during congestion) was 6710 veh/hr.

Assuming a 2% annual traffic growth along the M42-ATM section, it is expected that in 2015, traffic demand will exceed 6700 veh/hr for approximately 50% of the days (~193 days). This is likely to be within the AM Peak and PM-Peak periods. Probability analysis has shown that in 2019, flow-breakdown is likely to occur on ~13 days per year (3.6% per annum).

10.1.3. Factors which affect smart motorway operations

One of the aims of smart motorways is to improve the distribution of traffic between lanes. It is regarded that as traffic demand approaches close to capacity, lane utilisation across all lanes become more uniform; i.e. under ideal conditions, optimal utilisation of a motorway occurs when the traffic utilisation is equal across the individual running lanes.

Lane Utilisation

It was found that:

- When traffic flow is still low (i.e. during build-up), the majority of traffic are on Lanes 1 and 2.
- As traffic flows on the hard shoulder increases, and the lane utilisation on Lanes 1, 2 and 3 become very similar.
- Hard shoulder utilisation and proportion of traffic leaving at next junction are directly proportional to one another

Distribution of speed

It was important to understand how the introduction of VMSL had impacted this parameter as HSR aims to increase the observed motorway capacity by harmonising speed and thereby preventing the occurrence of flow-breakdown. The data confirmed that:

- motorists respond to the displayed speed limits and change their speeds during HSR operations.
- Speeds on the hard shoulder and Lane 1 were comparable for the 40 mph and 60 mph limit, and the speeds between the hard shoulder, Lane 1 and Lane 2 were comparable for the 50 mph limit.
- Standard deviation of average speeds for the 50 mph and 60 mph speed limits were smaller than compared to when the 40 mph limit

Multivariate analysis

A multivariate analysis was carried out to establish a model which described motorway capacity during smart motorway operations using various traffic parameters. A model was developed which used the following parameters:

- Lane Utilisation (HS)
- Lane Utilisation (Ln 1)
- Lane Utilisation (Ln 2)
- Speed_HS
- Speed_Ln1
- Speed_Ln2
- Proportion (%) of offslip flow

The r^2 for all signal settings considered were greater than 0.5, which is considered to be strong in statistical terms, providing a good estimate on motorway capacity during smart motorway operations.

10.2. The future of smart motorways

In the summer of 2014, a £15bn investment in infrastructure projects was announced by the Chief Secretary to the Treasury, Danny Alexander. This was later followed-up and confirmed with the announcement by David Cameron in Autumn 2014.

This programme outlines the Government's first long-term Road Investment Strategy, will result in over 100 projects being delivered across Highways England's strategic road network by the end of 2020, including 12 smart motorway schemes listed below. The operational concept design for each of these 12 schemes is to be delivered by the end of 2015.

- M3 Junction 9 – 14
- M27 Junction 4 - 11
- M23 Junction 8 – 10
- M20 Junction 3 – 5
- M1 Junction 24 – 25
- M1 Junction 13 – 16
- M6 Junction 2 – 4
- M6 Junctions 13 - 15
- M56 Junction 6-8
- M60 Junction 24-J4
- M62 Junction 10-12
- M6 Junction 21a-26

With the rapid roll-out of smart motorways across the UK, there will be a number of challenges for the designers to finalise the concept of operations for each scheme.

1. Influence of other schemes adjacent to the smart motorway scheme

As noted above, the Government's Road Investment Strategy announced Autumn 2014 will result in over 100 projects being delivered. These additional schemes would need to be assessed to understand whether they need to be included in full (or partially-included) into the design of a new smart motorway scheme, especially when carrying out traffic modelling exercises and making decisions on

the operational regimes to be implemented. As a result, establishing the scheme extents for the design work will be a key challenge within the design of future smart motorway schemes.

2. Interfaces between varying operational regimes

As discussed in previous chapters, although MM-ALR schemes are currently under design/construction, HSR and CM operations will still continue to be rolled-out on HA roads where MM-ALR is considered to not be a feasible solution (e.g. limited road space, required land space, availability of hard shoulder, etc.). It was noted within the previous chapters that:

- natural bottlenecks were formed on some existing smart motorway sections where the HSR section interfaced with a non-smart motorway section (i.e. dropping from 4 lanes to 3 lanes)
- changes in operational regimes within a route could also lead to driver confusion, making the signals/signs less intuitive to road users.

In addition, a junction within a newly proposed scheme may have an existing ramp metering site in operation, which may need to be re-evaluated as a result of smart motorways operation. Therefore the interfaces between varying operational regimes will need to be carefully considered to not compromise but optimise the benefits expected from the introduction of smart motorways.

3. Consistency across smart motorway schemes

With the rapid roll-out of smart motorways across the UK, there is a need for collaboration between Highways England, designers and other key stakeholders to achieve consistency within the smart motorway designs. Collaboration and knowledge share between the various parties will help to identify best practices to address the new challenges brought by the Government's new Road Investment Strategy.

10.3. Recommendations

The study within this research has examined a large dataset, the study has been limited to a number of smart motorway sites around Birmingham, UK due to the limited amount of smart motorway sites in operation at the time of writing. It is therefore recommended that the study is taken to expand the dataset, and to also incorporate additional variables such as physical features of the motorway and weather conditions (wet/dry/visibility).

In addition, the user consultation exercise identified a potential lack of understanding for this operational regime. Although this was an observation made through the analysis of TJR, this finding is highly applicable as smart motorways continue to evolve. If a driver were to travel along the Birmingham Box in the future, they would encounter various types of smart motorway operational regimes (HSR, TJR, CM, ALR), varying gantry spacings (500m, 800m then up to 1500m) and signal/sign configurations (as on ALR VMSL will not always be displayed above the running lane). Additional research will be required to ensure that the signals and signs are both intuitive to the motorist and to consider whether driver education will be required on how the various operational regimes work.

The findings from this research can be applied to assist in the application of smart motorways both in the UK and other countries.

List of references

References

Adams, R. (2007). *Active Traffic Management in the Netherlands: From reactive to pro-active traffic management*. [Online] Available at: <http://www.psrc.org/assets/541/ATMNetherlands6.21.07.pdf> [Last accessed: 29 April 2015].

Agarwal, M., Maze, T. H. and Souleyrette, R. (2005). Impacts of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity. *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*. Ames, Iowa. 18-19 August, 2005. Ames, Iowa : Center for Transportation Research and Education.

Berman, W., Differt, D., Aufschneider, K., DeCorla-Souza, P., Flemer, A., Hoang, L., Hull, R., Schreffler, E. and Zammit G. (2006). *Managing Travel Demand: Applying European Perspectives to U.S. Practice*. Report FHWA-PL-06-015. Published by the US Department of Transportation Federal Highway Administration, May 2006.

Blaney, T., Cusworth, R., and Ridding, C. S. (2011). *M42 MM Monitoring and Evaluation Three Year Safety Review*. Document Reference: 275509/ HWY/ TTS/ 002/ B.

Bracksonte, M., McDonald, M. and Wu, J. (1998). Lane changing on the motorway: factors affecting its occurrence and their implications. *Proceedings of the 9th International Conference on Road Transport Information and Control*. Institution of Electrical Engineers, London. 21-23 April, 1998. Institution of Electrical Engineers: London.

Bracksonte, M., Sultan, S. and McDonald, M. (2002). *Motorway driver behaviour: studies on car following*. Transportation Research Part F: Traffic Psychology and Behaviour. Vol. 5 (1) pp 31–46.

Brooks, R. M. (2010). Influence of vehicular interaction on PCU values. *Proceedings of the Institution of Civil Engineers: Transport*. 163(3) pp139-142.

Buckeye, K. R.(2009). User Perceptions of FEE Lane Concepts in Minnesota. [Online]Available at:
<http://www.coloradodot.info/projects/contextsensitivesolutions/docs/stakeholder-input/peak-period-shoulder-lanes-hard-shoulder-running/coloradodot-feelanes.pdf> [Last accessed: 29 April 2015].

Carlson, R. C., Papamichail, I., Papageorgiou, M., Messmer, A. (2010). Optimal Mainstream Traffic Flow Control of Large-Scale Motorway Networks. *Transportation Research Part C*. Vol 18(2010) pp193-212.

CEDR Task Group 09 (2009). VMS harmonisation in Europe. Published by Conference of European Directors of Roads.

Chase, P. and Avineri, E. (2008) Maximizing motorway capacity through hard shoulder running: UK perspective. *The Open Transportation Journal*. Vol 2(1) pp. 7-18.

Chin, C. H. (1996). Analysis of highway bottlenecks. *Proceedings of the Institution of Civil Engineers: Transport*. 117(2) pp136-142.

Chung, E., Ohtani, O., Warita, H., Kuwahara, M., and Morita, H. (2006). *Does Weather Affect Highway Capacity?* University of Tokyo Publications: Japan.

Cohen, S. (2004). Using the hard shoulder and narrowing lanes to reduce traffic congestion: some lessons from an experience on the Paris Motorway Network. *12th IEE International Conference on Road Transport Information and Control, 2004*. Institution of Electrical Engineers, London. 20-22 April 2004. Institution of Electrical Engineers: London.

Conference of European Directors of Roads (CEDR) Task Group 09 (2009). VMS harmonisation in Europe. Paris: Conference of European Directors of Roads.

Department for Transport (2000). *Transport Ten Year Plan 2000*. [Online] Available at:
<http://webarchive.nationalarchives.gov.uk/+http://www.dft.gov.uk/adobepdf/165259/tenyearplan> [Last accessed 11th April 2015].

Department for Transport (2007). *Towards a Sustainable Transport System: Supporting Economic Growth in a Low Carbon World*. [Online] Available at:
<http://webarchive.nationalarchives.gov.uk/+http://www.dft.gov.uk/about/>

[strategy/transportstrategy/pdfsustaintranssystem.pdf](http://www.dft.gov.uk/strategy/transportstrategy/pdfsustaintranssystem.pdf) [Last accessed 11th April 2015]

Department for Transport (2008a). *Advanced motorway signalling and traffic management feasibility study*. [Online] Available at: <http://www.dft.gov.uk/pgr/roads/network/policy/mtorsigntrafmanagement/advancedmotorwaysignal.pdf> [Last accessed: 21 June 2009]

Department for Transport (2008b). *Delivering a Sustainable Transport System: Main Report*. [Online] Available at: <http://webarchive.nationalarchives.gov.uk/+http://www.dft.gov.uk/about/strategy/transportstrategy/dasts/dastsreport.pdf> [Last accessed: 1 May 2010]

Department for Transport (2009a). *Road Statistics 2008: Traffic, Speeds and Congestion*.

Department for Transport (2009b). *Road Traffic and Congestion in Great Britain: Quarter 1 2009* [pdf]. London: Department for Transport. Available at: <http://www.dft.gov.uk/adobepdf/162469/221412/221546/224925/224965/466456/roadtraffgbq12009.pdf> [Last accessed 16 August 2009]

Department for Transport (2009c). *Road Traffic and Congestion in Great Britain: Quarter 4 2008* [pdf]. London: Department for Transport. Available at: <http://www.dft.gov.uk/adobepdf/162469/221412/221546/224925/224965/368305/roadtraffgbq408.pdf> [Last accessed 16 August 2009]

Department for Transport (2009d) *Transport Trends: 2008 Edition* [pdf]. London: Department for Transport. Available at: <http://www.dft.gov.uk/adobepdf/162469/221412/190425/220778/trends2008.pdf> [Last accessed 16 August 2009]

Department for Transport (2010). *Transport Trends 2009*. [pdf] available at: <http://www.dft.gov.uk/adobepdf/162469/221412/190425/220778/trends2009.pdf> [Last accessed 8 June 2010].

Department for Transport (2012). *Road traffic indices by road class in Great Britain, quarterly from 1993*. (9 February 2012) [xls] Available at: <http://assets.dft.gov.uk/statistics/tables/tra2503.xls> [Last accessed: 20 March 2012].

Design Manual for Roads and Bridges Vol. 13.1.5 (2002). *Economic Assessment of Road Schemes: Speed on Links*. Available at: <http://www.dft.gov.uk/pgr/economics/software/coba11usermanual/part5speedsonlinks.pdf> [Last accessed 03 August 2009]

Design Manual for Roads and Bridges (2005). TD27/05: *Cross-sections and Headrooms*. [pdf] available at: <http://www.standardsforhighways.co.uk/dmrb/vol6/section1/td2705.pdf> [Last accessed 12 June 2010]

Design Manual for Roads and Bridges (2006). TD22/06: Layout of Grade Separated Junctions. Available at: <http://www.standardsforhighways.co.uk/dmrb/vol6/section2/td2206.pdf> [Last accessed 03 August 2009]

Desnouailles, C. and Cohen, S (2007). Managed Lanes: A French project to Reduce Congestion on Motorway, *i2TERN Conference*. Aalborg Denmark: June 2007

Desnouailles, C., Boillon, P., Cohen, S., and Nouvier, J. (2007). Variable Lane Assignment: Two French projects for minimising congestion on urban motorways. [pdf] available at: <http://www.setra.equipement.gouv.fr/IMG/pdf/ip296-e.pdf> [Last accessed 01 July 2010],

Dhingra, S.L. and Gull, I. (2008). Traffic Flow Theory Historical Research Perspectives. *Greenshields 75 Symposium*. Transportation Research Board: 8-10 July 2008. Massachusetts.

Diels, C., Reed, N., and Parkes, A. M. (2009). *Evaluation of novel motorway designs using driver simulation*. Association for European Transport and contributors 2009.

Easyway (2009). *Guideline for the Deployment of Hard Shoulder Running*. Easyway: Core European ITS Services and Actions (Report Number TMS-DG04).

Eddington, R (2006). The Eddington Transport Study, Department for Transport. [online] available at: <http://webarchive.nationalarchives.gov.uk/+http://www.dft.gov.uk/about/strategy/transportstrategy/eddingtonstudy/> [Last accessed:27 March 2010].

Edwards, J. B. (1999). Speed adjustment of motorway commuter traffic to inclement weather. *Transportation Research Part F*. Vol 2 (1999) pp 1-4.

Elefteriadou, L. and Lertworawanich, P. (2003). *Defining, measuring and estimating freeway capacity*. 82nd TRB Annual Conference, Washington DC.

Geistefeldt, J. (2008) Empirical Relation Between Stochastic Capacities and Capacities Obtained from the Speed-Flow Diagram. Symposium on the Fundamental Diagram: 75 Years. Woods Hole, MA. USA.

Gibbens, R.J. and Saacti, Y. (2006). *Road traffic analysis using MIDAS data: journey time prediction*. University of Cambridge Computer Laboratory Technical Report TR-676.

Greenshields, B. D. (1935). *A Study of Traffic Capacity*. Highway Research Board Proceedings, Vol. 14 (1935) pp. 448-477.

Grontmij (2010). *Grontmij drives motorway management* [online] available at: <http://www.grontmij.ie/mediacentre/news/Pages/motorwaymanagement.aspx> [Last accessed 16 August 2010]

Gunay, B. (2004). An investigation of lane utilisation on Turkish highways. *Proceedings of the Institution of Civil Engineers. Transport* 157 (1) pp43-49.

Hall, F., Montgomery, F. O. (1993). The investigation of an alternative interpretation of the speed-flow relationship for UK motorways. *Traffic Engineering & Control*. Vol 34 (9) pp. 420 – 425.

Hampton, K., Mills, C., Doherty, D. and Arlow, A. (2012). *BBMM Phase 1&2 Monitoring and Evaluation: Milestone 3 Phase 2 Air Quality Monitoring Report*. Produced by Mott MacDonald Grontmij JV on behalf of the Highways Agency. Unpublished document.

Harbord, B. (1998). M25 controlled motorway - results of the first two years. *9th International Conference on Road Transport Information and Control*. 21-23 April 1998. Conference Publication 454 pp149 – 154.

Harbord, B., Abou-Rahme, N., Beale, S. and Hardman, E. (2000) Monitoring and modelling of controlled motorways. *10th International Conference on Road Transport Information and Control*. 4-6 April 2000. Conference Publication 472 pp84-90.

Helleman, B (2005). *Managed Lanes in the Netherlands: an overview of TMS applications*. [presentation] Available at: <http://www.trb-freewayops.org/reports/86th%20Annual%20Meeting%20-%20January%2021-25,%202007/Session%20203/Managed%20Lanes%20in%20Netherlands%20Bert%20Helleman.pdf> [Last accessed 15 August 2009]

Heslop, S., Harvey, J., Thorpe, N. and Mulley, C. (2014). *The influence of personal variables on changes in driver behaviour*. Safety, Reliability and Risk Analysis: Theory, Methods and Applications Volume 1. Taylor & Francis Group, London.

Heydecker, B. G. and Addison, J. D. (2008). Measuring traffic flow using real-time data. *75 Years of the Fundamental Diagram for Traffic Flow Theory*. Transportation Research Circular E-C 149, pp109-120.

Heydecker, B. G. and Addison, J. D. (2011). Emerging theories in traffic and transportation and methods for transportation planning and operations. *Transportation Research Part C: Emerging Technologies*. Vol 19(2) pp206-217.

Highways Agency (2005). *Detector Loops for Motorways*. Document Reference: HD20/05.

Highways Agency (2009a). M42 Junction 5 Hard Shoulder Through Junction Running. [online] available at: <http://www.highways.gov.uk/knowledge/24248.aspx> [Last accessed: 01 September 2010]

Highways Agency (2009b). Managed Motorways implementation guidance: Hard Shoulder Running. Interim Advice Note 111/09. Highways Agency Publications. [pdf] available at: http://www.standardsforhighways.co.uk/ians/pdfs/ian111_09.pdf [Last accessed 02 September 2010]

Highways Agency (2009c). Strategic plan: 'the world's leading road operator'. Highways Agency publication. [pdf] available at: http://www.highways.gov.uk/aboutus/documents/NPPD_Strategic_Plan_-_Final1.pdf [Last accessed 02 September 2010]

Highways Agency (2009d): Business Plan 2009-2010. [pdf] available at: http://www.highways.gov.uk/aboutus/documents/Business_Plan_09-10_Web_Version.pdf [Last accessed 02 September 2010]

Highways Agency (2009e). NMCS2 MIDAS Subsystem Specification. Ref: TR2144, Issue J August 2009.

Highways Agency (2012). Managed Motorways – Dynamic Hard Shoulder (MM-DHS) Concept of Operations.

Highways Agency (2012). Managed Motorways All lanes running. Interim Advice Note 161/12.

Holt, A. (2009). Managed Motorways: A Change In Policy Equals A Reduction In Carbon. Smart Environment Interest Group Conference 2009. ITS UK, London.

Holt, A. and Conquest, J. (2009). Managed Motorways: Driving Change. *Thinking Highways*. Vol 4 (3) pp 48-52.

Hounsell, N. and McDonald, M. (1992). *An Investigation of Flow Breakdown and Merge Capacity on Motorways*. Contractor Report 338, Transport Research Laboratory: UK

Hounsell, N. B., Barnard, S. R., McDonald, M (1994). Capacity and Flow Breakdown on UK Motorways. *Proceedings of the Second International Symposium on Highway Capacity*. Vol 1, pp 277-294.

- Kerner, B.S. (2004). Three-phase traffic theory and highway capacity. *Physica A: Statistical and Theoretical Physics*. Vol 333:February 2004, pp379-440.
- Kim, Y. and Keller, H. (2008). Analysis of Characteristics of the Dynamic Flow- Density Relation and its Application to Traffic Flow Models. *Transportation Planning and Technology*. Vol. 31(4) pp369-397.
- Lamnitzer and Simpson (2012). Managed Motorways – Experience from the UK. Conference of the Transportation Association of Canada.
- Lewis-Evans, B., de Waard, D. and Brookhuis, K. A. (2011). *Speed maintenance under cognitive load – Implications for theories of driver behaviour*. *Accident Analysis & Prevention*. Vol. 43 (4) pp 1497–1507.
- M6toll (2013). History. [online] Available at: <https://www.m6toll.co.uk/>
- Middleham, F. (2006). State of Practice In Dynamic Traffic Management in The Netherlands.
- Mirshashi, M., Obenberger, J., Fuhs, C. A., Howard, C. E., Krammes, R. A., Kuhn, B. T., Mayhew, R. M., Moore, M. A., Sahebjam, K., Stone, C. J., and Yung, J. L. (2007). *Active Traffic Management: The Next Step in Congestion Management*. Federal Highway Administration. [pdf] Available at: <http://international.fhwa.dot.gov/pubs/pl07012/> [Last accessed: 06 July 2010]
- Monk-Steel, A., Forni, M., Doherty, D. and Arlow, A.J. (2012). *BBMM Phase 1&2 Monitoring and Evaluation: Milestone 3 Phase 2 After Construction Noise Data Analysis Report*. Produced by Mott MacDonald Grontmij JV on behalf of the Highways Agency. Unpublished document.
- Morris, B., Notley, S., Boddington, K, and Rees, T. (2011). External Factors Affecting Motorway Capacity. *Procedia – Social and Behavioral Sciences*. Vol 16 (2011) pp 69-75.
- Mott MacDonald (2011). BBMM 1&2 Year 3: BBMM1 Summary Report. March 2011.
- Mouchel (2008). M42 Active Traffic Management: Investigation into the operational impact of hard shoulder running at 60 mph. Document ref: 42691/DOC/0398 rev A.
- Nielsen, O.A and Jorgensen, R.M. (2008). Estimation of speed-flow and flow density relations on the motorway network in the greater Copenhagen region. *IET Intelligent Transport Systems*. Vol. 2(2) pp 120-131.

O'Brien, E., Lipari, A. and Caprani, C. (2011). Estimation of Density and Gaps in Congested Traffic. *Proceedings of the ITRN 2011*. 31st August – 1st September 2011. University College Cork.

Ogawa, J. (2009a). Monitoring and Evaluation of Managed Motorway Schemes: EngD 12 month report. University of Southampton (internal report).

Ogawa, J., Poole, A., Sultan, B., and Meekums, R. (2009b). *M42 ATM Monitoring and Evaluation: HSR60 6 month operation report*. Mott MacDonald. [pdf] available at: <http://www.highways.gov.uk/knowledge-compendium/assets/documents/Portfolio/HSR60%20Report%20-%201254.pdf> [Last accessed: 7 August 2010]

Ogawa, J., Poole, A., and Arlow, AJ. (2011a). *BBMM 1&2 Monitoring and Evaluation: Milestone 1 Traffic Data Analysis: BBMM1 'After' Case Status Report*. Mott MacDonald: January 2011.

Ogawa, J., Poole, A., and Arlow, AJ. (2011b). *Managed Motorway Monitoring and Evaluation of Through Junction Running and Safety: M42 J5 Through Junction Running Evaluation*. Mott MacDonald: January 2011.

Ogawa, J., Poole, A., and Arlow, AJ. (2012a). *BBMM Phase 1&2 Monitoring and Evaluation: BBMM2 Summary Report*. Mott MacDonald Grontmij JV: April 2012.

Ogawa, J., Poole, A., and Arlow, AJ. (2012b). *BBMM Phase 1&2 Monitoring and Evaluation: Milestone 1 Phase 2 After Construction Traffic Data Analysis Report*. March 2012.

Ogawa, MJ., Poole, AJ., Meekums, RJ., Cooke, D., and Self, S. (2012). *Managed Motorways: Keeping Business Moving*. *19th ITS World Congress*, 22-26th October 2012. Vienna.

Organisation for Economic Cooperation and Development (1983). *Traffic capacity of Major Routes*. Paris: 1983.

Organisation for Economic Cooperation and Development (2010). *Improving Reliability on Surface Transport Networks*. UK: European Conference of Ministers of Transport.

Rijksoverheid (2013). *Wat is de maximumsnelheid voor het wegverkeer? (what is the speed limit for road traffic)*. [online] Available at: <http://www.rijksoverheid.nl/onderwerpen/wegen/vraag-en-antwoord/wat-is-de-maximumsnelheid-voor-het-wegverkeer.html>

- Simpson, A and Kamnitzer, K. (2010). Operational Challenges of Managed Motorways. *RTIC 2010 Conference Paper*, 25-27 May 2010 pp1-5.
- Sisiopiku, V., Sullivan, A. and Fadel, G. (2009). *Implementing Active Traffic Management Strategies in the U.S.* University Transportation Center for Alabama. Report o8206.
- Slinn, M. (2005), *Traffic Engineering Design: Principles and Practice*. A Butterworth-Heinemann Title (2nd ed). London.
- Sparmann, J (2007). *Active Traffic Management Experiences Made in Hessen*. [Presentation] Available at: <http://www.psrc.org/assets/534/ATMinHessen6.07.pdf> [Last accessed 06 July 2010].
- Staufreies Hessen (2010). *Staufreies Hessen 2015. Temporary use of hard shoulders*. [Online] available at: http://www.staufreieshessen.de/irj/Staufrei_Internet?cid=0a2f13f725e7a72b617731ca75edd3cb [Last accessed 01 July 2010].
- Sultan, B., Poole, A., Meekums, R. and Potter, R. (2008). *ATM Monitoring and Evaluation, 4-Lane Variable Mandatory Speed Limits 12 Month Report (Primary and Secondary Indicators)*. Published by Department of Transport, July 2008.
- Summersgill, I., Kennedy, J. V., Sharples, J. M. and Frew, M. J. (2004). *Safety on Hard Shoulders on Dual Two-Lane and Three-Lane Motorways*. Published Project Report PPR017.
- Taylor, N., Bourne, N., Notley, S. and Skrobanski, G. (2008). *Evidence for Speed Flow Relationships*. European Transport Conference 2008.
- Toffin, E. (2004). *Intelligent Hard Shoulder: When Congestion Relief Meets Safety*. *ITE 2004 Annual Meeting and Exhibit*. Florida, 1-4 August 2004. Institute of Transportation Engineers.
- Toffin, E. (2008). *The Fifth Amendment*. Thinking highways. [pdf] Available at: [http://www.citilog.fr/pdfs/Thinking%20Highways%20-%205th%20Amendment%20\(Intelligent%20Hard%20shoulder\)%20-%20jan08.pdf](http://www.citilog.fr/pdfs/Thinking%20Highways%20-%205th%20Amendment%20(Intelligent%20Hard%20shoulder)%20-%20jan08.pdf) [Last accessed: 06 July 2010]
- Transportation Research Board (2000). *Highway Capacity Manual 2000*. USA
- Ungermah, D. and Kuhn, B (2009). *Special Use of Shoulders for Managed Lanes: Review of Practice and Research*. Texas Transportation Institute

United Nations Economic Commission for Europe (2003). Netherlands: Transport Situation in 2003. [pdf] available at: <http://www.unece.org/trans/doc/transsitdocs/2003netherlands.pdf> [Last accessed: 06 July 2010]

Unwin, P. and Marsh, P. (2009). ATM to Managed Motorways: delivering operational benefits to road users through the introduction of innovative technology solutions. Association for European Transport and Contributors 2009.

Van Vuren, T., Baker, J., Ogawa, M., Cooke, D., and Unwin, P. (2012). Managed Motorways: Modelling and Monitoring their Effectiveness. Transportation Research Record, No. 2278 pp85-94. Transportation Research Board, Washington.

Warita, Hl, Okamura, H., Morita, H., Kuwahara, M., Chung, E (2006). Analysis of Road Potential and Bottlenecks Based on Operating Speed. International Journal of ITS Research. Vol 4(1).

Wilson, R.E. (2008). Mechanisms for spatio-temporal pattern formation in highway traffic models. *Philosophical Transactions of the Royal Society A*. Vol 366 pp 2017-2032.

Wu, N. (2006). Equilibrium of Lane Flow-Distribution on Motorways. *Transportation Research Record: Journal of the Transportation Research Board*. Vol 1965 pp48-59.

Bibliography

Ball, S. D. (2010). *Identifying ITS Opportunities for the HA. Managed Motorways Fact Sheet: February 2010*. ITS Radar International. UK.

Crantson, R., Curry, A. and Hobbs, E. (2010). *Delivering Managed Motorway information to In-Vehicle Devices: Analysis Report*. Published by Department of Transport, May 2010.

Daganzo, C. F. (2000). *A Behavioral Theory of Multi-Lane Traffic Flow Part I: Long Homogeneous Freeway Sections*. University of California at Berkeley Research Report UCB-ITS-RR-99-5.

Dureta, A., Ahn, S. and Buisson, C. (2012). Lane flow distribution on a three-lane freeway: General features and the effects of traffic controls. *Transportation Research Part C: Emerging Technologies*. Vol 24 (2012) pp157-167.

Gibbens, R. J. and Saatci, Y. (2008). Data, modelling and inference in road traffic networks. *Philosophical Transactions of the Royal Society A*. Vol 366 pp 1907-1919.

Hall, F. L. (1987). An Interpretation of Speed-Flow-Concentration Relationships Using Catastrophe Theory. *Transportation Research Part A*. Vol 21A (3) pp191-201.

Invensys Rail Group (2007). *A Comparison of the Costs of Different Methods of Increasing Capacity in Road & Rail Environments*. Transport Capacity Research Paper Issue 1/2007.

Kockelman, K.M. (1998). *Changes in the Flow-Density Relation due to Environmental, Vehicle and Driver Characteristics*. Transportation Research Record 1644. Washington DC: Transportation Research Board.

Kuhn, B. (2008). Managed Lanes and Active Traffic Management: future trends in congestion management. *Smart Traffic 2008*. Brisbane 29-30 October 2008. Transport Roundtable Australasia: Australia.

Maerivoet, S. and De Moore, B. (2008). *Traffic Flow Theory*. Katholieke Universiteit Leuven: Belgium.

Murray, P., Mahmassani, H.S., Abdelghany, A. and Handy, S. (2000). *Defining Special Use Lanes: Case Studies and Guidelines*. Texas Department of Transportation (Report Number 0-1832-1).

Papageorgiou, M., Blosseville, J. and Hadi-Salem, H. (1989). Macroscopic Modelling of Traffic Flow on the Boulevard Peripherique in Paris. *Transportation Research Part B*. Vol 23B(1) pp29-47.

Park, B., Zhang, Y. and Lord D. (2010). Bayesian Mixture Modeling Approach to Account for Heterogeneity in Speed Data. *Transportation Research Part B: Methodological*. Vol 44(5) pp 662-673.

Transportation Research Board (2003). Judicial Enforcement of Variable Speed Limits. *NCHRP Legal Research Digest*. No. 47. Transportation Research Board: Washington DC.

Ungemah, D., Kuhn, B. and Baker, T. (2008). *State of the Practice for Managed Use Lane Projects*. Texas Transportation Institute (TTI), Parsons Brinckerhoff (PB), New York State Department of Transportation (NYSDOT): 2008.

Waller, S. T., Ng, M., Ferguson, E., Nezamuddin, N., and Sun, D. (2009). Speed Harmonization and Peak-period Shoulder Use to Manage Urban Freeway Congestion. Center for Transportation Research, Texas. (Report Number 0-5913-1)

Williams, B. M., and Hoel, L. A. (2003). Modeling and Forecasting Vehicular Traffic Flow as a Seasonal ARIMA Process: Theoretical Basis and Empirical Results. *Journal of Transportation Engineering*. Vol 129 (6) pp664-672.

Wu, N. and Lemke, K. (2011). A new Model for Level of Service of Freeway Merge, Diverge, and Weaving Segments. *Procedia Social and Behavioral Sciences*. Vol 16(2011) pp151-161.

Appendices

Appendix A: Sample of Traffic Data Analysis Macro

Appendix A.1: MIDAS

Appendix A.2: HALOGEN MACRO

Appendix B: User Consultation Questionnaire

Appendix C: Analysis days for the video footage analysis

Appendix D: Lane Utilisation during HSR operations

Appendix E: Hard shoulder utilisation vs proportion of traffic leaving at next junction

Appendix A: Sample of Traffic Data Analysis Macros

Appendix A.1: MIDAS data extraction macro

(only presenting part of the code where traffic data is extracted)

```
Public retval
```

```
Sub Binary(i, file$)
```

```
Dim nFileNum As Integer, nNumber As Byte
```

```
nFileNum = FreeFile
```

```
Open file$ For Binary Access _
```

```
    Read Lock Read Write As #nFileNum
```

```
Get #nFileNum, i, nNumber
```

```
retval = nNumber
```

```
Close #nFileNum
```

```
End Sub
```

```
Sub Call_all_loops()
```

```
Application.ScreenUpdating = False
```

```
'***** input data *****
```

```
file_dir$ = Sheets("INFO").Cells(2, 2)
```

```
Anal_year$ = Sheets("INFO").Cells(3, 2)
```

```
CO$ = Sheets("INFO").Cells(4, 2)
```

```
'***** non-looping data *****
```

```
File_dr$ = Left(file_dir$, 1)
```

```
Sheets("INFO").Cells(10, 2) = File_dr$
```

```
'***** looping data *****
```

```
'MIDAS loops!
```

```
For i = 2 To 13 'MIDAS loops listed in column E, change list as required
```

```
    Sheets("INFO").Cells(7, 2) = Sheets("INFO").Cells(i, 5)
```

```
    Loops$ = Right(Sheets("INFO").Cells(7, 2), 5)
```

```
'months in year
```

```
    For m = 1 To 12
```

```
        Sheets("INFO").Cells(8, 2) = m
```

```
        mths$ = m
```

```
        If m < 10 Then
```

```
            txtm$ = "0" + mths$
```

```
            mths$ = Right(txtm$, 2)
```

```
        End If
```

```

'days in month
Days_in_Mth$ = Day(DateSerial(Anal_year$, m + 1, 1) - 1)
For d = 1 To Days_in_Mth$
    Sheets("INFO").Cells(9, 2) = d
    dates$ = d

    If d < 10 Then
        txtD$ = "0" + dates$
        dates$ = Right(txtD$, 2)
    End If

    Anal_Date$ = (DateSerial(Anal_year$, m, d))
    Anal_Month$ = MonthName(m)

    file_name$ = CO$ + dates$ + mths$ + Right(Anal_year$, 2) + ".tcd"
    Sheets("INFO").Cells(11, 2) = file_name$

    file_path$ = file_dir$ + "\" + Anal_year$ + "\CO" + CO$ + "\" +
Anal_Month$ + "\" + file_name$
    Sheets("INFO").Cells(12, 2) = file_path$

***** open files and read data *****
'with HS or no HS?
If Sheets("INFO").Cells(5, 2) = "Y" Then
    x = 4
Elseif Sheets("INFO").Cells(5, 2) = "N" Then
    x = 3
End If

Sheets("1min").Select

ChDrive Sheets("INFO").Cells(10, 2)
ChDir Sheets("INFO").Cells(2, 2)
filename$ = Sheets("INFO").Cells(11, 2)

'define sheet position
day2 = DateSerial(Anal_year$, m, d + 1)
day1 = DateSerial(Anal_year$, 1, 1)
Date_cnt = day2 - day1

sht_pos$ = 1 + 1440 * (Date_cnt - 1)

Cells(sht_pos$ + 1, 1).Value = Anal_Date$

***** Flow *****
If x = 4 Then
    For l = 1 To x
        lanes$ = l
    
```

```

        Call readcnt(Loops$, filename$, sht_pos$, lanes$)

    Next l

End If

If x = 3 Then
    For l = 1 To x

        Next l

    End If

'***** Speed *****
If x = 4 Then
    For l = 1 To x

        'Call readspd(Loops$, filename$, i)
        Next l

    End If

If x = 3 Then
    For l = 1 To x

        Next l

    End If
,
Next d
Next m
Next i

Cells(1, 1).Select

End Sub

Sub readcnt(Loops$, filename$, sht_pos$, lanes$)
'loop1$ , file$

i = 19
1000:
Dim nFileNum As Integer, nloop As String
nFileNum = FreeFile
Open filename$ For Binary Access _

```

Read Lock Read Write As #nFileNum

```
nloop = Space$(12)
Get #nFileNum, i, nloop
Close #nFileNum
Do While Left(nloop, 1) = " "
nloop = Right(nloop, Len(nloop) - 1)
Loop
```

```
Do While Right(nloop, 1) = " "
nloop = Left(nloop, Len(nloop) - 1)
Loop
i = i + 16
```

```
Call Binary(i, file$)
nlanes = retval
```

```
Do Until loop1$ = Right(nloop, Len(nloop) - 1) 'if the right loop
i = i + (1440 * (8 + (nlanes * 5))) + 1 'lets see if this works
GoTo 1000:
Loop
```

```
Cells(1, 1) = loop1$
'headers
For c3% = 1 To nlanes
Cells(2, c3%) = "lane" + Right(Int(c3%), 1)
Next c3%
```

```
k = 2
For c1% = 1 To 1440
l = 1
i = i + 8
k = k + 1
For c2% = 1 To nlanes
i = i + 3
```

```
Call Binary(i, file$)
```

```
If retval = 255 Then retval = "" 'error = blank
```

```
Cells(k, l) = retval
l = l + 1
i = i + 2
Next c2%
```

```
Next c1%
```

```
'Cells(1, 1) = nNumber
```

```
End Sub
```

Appendix A.2: HALOGEN MACRO

‘extracts Halogen signal data (speed settings)

Table 41: Extract of raw Halogen Data

Logging_System	Date_and_time	Equipment_Type	Equipment_Ref	Equipment_Setting	Initiator_Id_Type	Initiator_Id	Implementation_Reason	Setting_Status	Requested_Setting
West Midlands ATM	01/09/2006 00:07 SIG		M42/6377B2	NR	AUTO	MID	ROAD WORKS-CONING		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6377B3	NR	AUTO	MID	ROAD WORKS-CONING	FAULTY	
West Midlands ATM	01/09/2006 00:07 SIG		M42/6377B4	NR	AUTO	MID	ROAD WORKS-CONING		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6370B2	RE	AUTO	MID	UPDATE/INITIALISATION		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6370B3	RE	AUTO	MID	UPDATE/INITIALISATION		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6370B4	RE	AUTO	MID	UPDATE/INITIALISATION		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6368M1	RE	AUTO	MID	CONGESTION		
West Midlands ATM	01/09/2006 00:07 SIG		M42/6368M2	RE	AUTO	MID	CONGESTION	FAULTY	
West Midlands ATM	01/09/2006 00:10 SIG		M42/6370B1	BLNK	AUTO	HSM	UPDATE/INITIALISATION	FAULTY	
West Midlands ATM	01/09/2006 01:08 SIG		M42/6431A1	40R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6431A2	40R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6431A3	40R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6431K1	40R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6427A1	REDX	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6427A2	50R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6427A3	50R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6427A4	50R	AUTO	MID	INCIDENT		
West Midlands ATM	01/09/2006 01:08 SIG		M42/6424K1	50R	AUTO	MID	INCIDENT		

Sub run()

```
Call read_HALOGEN
Call filter_15_full
Call filter_15_wgt
```

```
End Sub
```

```
Sub clear()
    Sheets("status").Select
    Range(Cells(2, 2), Cells(44641, 10)).Select

    Selection.ClearContents
    Selection.Interior.ColorIndex = xlNone
```

```
End Sub
```

```
Sub read_HALOGEN()
Application.ScreenUpdating = False
Call clear
```

```
'*****prepare time*****
Sheets("HALOGEN LOG").Select
DinMth$ = DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)) + 1, 1) -
DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)), 1) 'returns # days in mth
```

```
Sheets("status").Select
Range(Cells(2, 1), Cells(1441, 1)).Select
Selection.Copy
Range(Cells(2, 1), Cells(1441 + 1440 * DinMth$, 1)).Select
ActiveSheet.Paste
Application.CutCopyMode = False
```

```
'*****filter for loop*****
For i = 3 To 10
    Sheets("status").Select
    Gantry$ = Cells(1, i).Text
    Sheets("HALOGEN LOG").Select

    Columns("D:D").Select
    Selection.AutoFilter
    Selection.AutoFilter Field:=1, Criteria1:=Gantry$
```

```
Cells(2, 5).Select 'first log of halogen
```

```
CI = 2 'colour index white
```

```
If Right(Gantry$, 1) = "1" Then
    limit = 1 'blank
Else
    limit = 70 '70 mph
```

```
End If
```

```

'loop here to find next hidden cell
Do Until ActiveCell.Rows.Hidden = False
    ActiveCell.Offset(1, 0).Select
Loop

dayflag = 1

Do Until ActiveCell = ""

HSRday$ = DateValue(ActiveCell.Offset(0, -3))
Dates$ = CInt(Left(HSRday$, 2))
Sheets("Status").Select
Range(Cells(2 + 1440 * (Dates$ - 1), 2), Cells(1441 + 1440 * (Dates$ - 1), 2)) =
DateValue(HSRday$)

Sheets("HALOGEN LOG").Select
HSRmin1 = (Mid(ActiveCell.Offset(0, -3), 12, 2) * 60) +
Mid(ActiveCell.Offset(0, -3), 15, 2) + 1440 * (Dates$ - 1)

'*****
If dayflag = 1 Then 'write out min1 to HSRmin1

For j = 1 + 1440 * (Dates$ - 1) To HSRmin1 'minutes

Sheets("Status").Cells(j + 1, i).Interior.ColorIndex = CI
Sheets("Status").Cells(j + 1, i) = limit

Next j
dayflag = 0
End If
'*****

Select Case ActiveCell.Text 'select colour

Case "RE", "OFF", "NR"
CI = 2 'white
limit = 70

Case "BLNK"
CI = 2 'white
limit = 1

Case "REDX"
CI = 38
limit = 2

Case "STOP"
CI = 3
limit = 3

```

Case "60R"
CI = 4 'green
limit = 60

Case "50R"
CI = 46 'orange
limit = 50

Case "40R"
CI = 6 'yellow
limit = 40

Case "30R", "20R", "10R"
CI = 39 'Purple
limit = 30

End Select

'*****

ActiveCell.Offset(1, 0).Select
Do Until ActiveCell.Rows.Hidden = False
ActiveCell.Offset(1, 0).Select
Loop

Sheets("HALOGEN LOG").Select
If ActiveCell.Offset(0, -3) <> "" Then

 If HSRday\$ = DateValue(ActiveCell.Offset(0, -3)) Then 'sameday
 HSRmin2 = (Mid(ActiveCell.Offset(0, -3), 12, 2) * 60) +
Mid(ActiveCell.Offset(0, -3), 15, 2) + 1440 * (Dates\$ - 1)
 Else 'not the same day
 dayflag = 1
 HSRmin2 = 1441 + 1440 * (Dates\$ - 1)
 End If

Else
 dayflag = 1
 HSRmin2 = 1441 + 1440 * (Dates\$ - 1)
End If

For j = HSRmin1 To HSRmin2 'minutes
 Sheets("Status").Cells(j + 1, i).Interior.ColorIndex = CI
 Sheets("Status").Cells(j + 1, i).Value = limit
Next j

'ActiveCell.Offset(1, 0).Select 'find next signal

Loop 'all halogen log

Selection.AutoFilter

```

'select status sheet
Sheets("Status").Select

Next i

Application.ScreenUpdating = True

End Sub

Sub filter_15_full()
'only records if same speed setting was implemented for the full 15 min
period

'*****prepare time*****
Sheets("status").Select
DinMth$ = DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)) + 1, 1) -
DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)), 1) 'returns # days in mth

Sheets("15 min (1)").Select
Range(Cells(2, 1), Cells(97, 1)).Select
Selection.Copy
Range(Cells(2, 1), Cells(97 + 96 * DinMth$, 1)).Select
ActiveSheet.Paste
Application.CutCopyMode = False

'*****method 1*****
Sheets("status").Select

DinMth$ = DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)) + 1, 1) -
DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)), 1)

For j = 3 To 10 'gantry
  For i = 1 To 96 * DinMth$

    If j = 3 Then
      Sheets("15 min (1)").Cells(i + 1, 1) = Cells(2 + 15 * (i - 1), 1).Value 'time
      Sheets("15 min (1)").Cells(i + 1, 2) = Cells(2 + 15 * (i - 1), 2).Value 'date
    End If

    Dim Min_15 As Range
    Set Min_15 = Range(Cells(2 + 15 * (i - 1), j), Cells(16 + 15 * (i - 1), j)) '15
min range

    If 15 - Application.CountIf(Min_15, 40) = 0 Then
      Sheets("15 min (1)").Cells(i + 1, j) = 40

    ElseIf 15 - Application.CountIf(Min_15, 50) = 0 Then
      Sheets("15 min (1)").Cells(i + 1, j) = 50

    ElseIf 15 - Application.CountIf(Min_15, 40) = 0 Then

```

```

    Sheets("15 min (1)").Cells(i + 1, j) = 60

    Else
    Sheets("15 min (1)").Cells(i + 1, j) = 0

    End If

    Next i
Next j

End Sub

Sub filter_15_wgt()
'HSR in operation for full 15 min, but if more than one signal was used, then
take average

'*****prepare time*****
Sheets("status").Select
DinMth$ = DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)) + 1, 1) -
DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)), 1) 'returns # days in mth

Sheets("15 min (2)").Select
Range(Cells(2, 1), Cells(97, 1)).Select
Selection.Copy
Range(Cells(2, 1), Cells(97 + 96 * DinMth$, 1)).Select
ActiveSheet.Paste
Application.CutCopyMode = False

'*****method 2*****
Sheets("status").Select

DinMth$ = DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)) + 1, 1) -
DateSerial(Year(Cells(2, 2)), Month(Cells(2, 2)), 1)

For j = 3 To 10 'gantry
    For i = 1 To 96 * DinMth$

        If j = 3 Then
            Sheets("15 min (2)").Cells(i + 1, 1) = Cells(2 + 15 * (i - 1), 1).Value 'time
            Sheets("15 min (2)").Cells(i + 1, 2) = Cells(2 + 15 * (i - 1), 2).Value 'date
            End If

        Dim Min_15 As Range
        Set Min_15 = Range(Cells(2 + 15 * (i - 1), j), Cells(16 + 15 * (i - 1), j)) '15
min range

        If 15 - Application.CountIf(Min_15, 40) - Application.CountIf(Min_15, 50)
- Application.CountIf(Min_15, 60) = 0 Then
            Sheets("15 min (2)").Cells(i + 1, j) = Application.Mode(Min_15)

        Else

```

```
Sheets("15 min (2)").Cells(i + 1, j) = 0
```

```
End If
```

```
Next i
```

```
Next j
```

```
End Sub
```

Appendix B: User Consultation Questionnaire

Motorway Users Survey

Good morning/afternoon/evening. My name is ... and I am undertaking research for Mott MacDonald Ltd on behalf of the Highways Agency into motorway travel in the Birmingham area. The survey takes about 10 minutes. Any answers you give will be treated in confidence in accordance with the Market Research Society Code of Conduct. You do not have to answer any questions you do not wish to and you can terminate the interview at any time. Are you willing to take part?

Q1 Have you driven along this motorway section IN THE PAST THREE MONTHS? (SHOWCARD A)

- M6 J8 - J10A
 None of the above

GO TO Q3
 THANK & CLOSE

Q2 How often do you usually use this section as a driver or motorcycle user?

- 5 days or more (FREQUENT)
 2-4 days (FREQUENT)
 Once a week (INFREQUENT)
 Less than once a week (INFREQUENT)
 Once a month (INFREQUENT)
 Less than once a month (INFREQUENT)
 First time today (INFREQUENT)

Q3 FREQUENT: Which of these sections do you also typically use?
 INFREQUENT: Which of these sections did you also drive along on your last trip?

- A B C None of those

Q4 FREQUENT: On your outward journey, where do you usually join and exit the motorway?
 INFREQUENT: On your outward journey, where did you join and exit the motorway?

- | | Join | Exit |
|--|--------------------------|--------------------------|
| A - C | <input type="checkbox"/> | <input type="checkbox"/> |
| D | <input type="checkbox"/> | <input type="checkbox"/> |
| None of the above - just drive through | <input type="checkbox"/> | <input type="checkbox"/> |

Q5 FREQUENT: On your return journey, where do you usually join and exit the motorway?
 INFREQUENT: On your return journey, where did you join and exit the motorway?

- | | Join | Exit |
|--|--------------------------|--------------------------|
| A - C | <input type="checkbox"/> | <input type="checkbox"/> |
| D | <input type="checkbox"/> | <input type="checkbox"/> |
| None of the above - just drive through | <input type="checkbox"/> | <input type="checkbox"/> |

I would like you now to think specifically about the M6 J8 - J10A (SECTION D).

Q6 FREQUENT: At what times of day do you typically drive along this section?
 INFREQUENT: At what times of the day was your most recent trip along this section?

- | | Outward Journey | Return Journey |
|------------------------------|--------------------------|--------------------------|
| Before 7am | <input type="checkbox"/> | <input type="checkbox"/> |
| 7am to 10am | <input type="checkbox"/> | <input type="checkbox"/> |
| After 10am but before 3.30pm | <input type="checkbox"/> | <input type="checkbox"/> |
| 3.30pm to 7pm | <input type="checkbox"/> | <input type="checkbox"/> |
| After 7pm | <input type="checkbox"/> | <input type="checkbox"/> |

Q7 **FREQUENT:** On which days do you usually drive along this section?
INFREQUENT: On which day was the last trip you made along this section?

TICK ALL THAT APPLY

- Monday to Friday Saturday and Sunday Don't know / Can't remember

Q8 **FREQUENT:** For what purpose do you mainly travel along this section?
INFREQUENT: What is the main purpose for your journey?

TICK ONE ONLY

- Commuting to/from work
 Commuting to/from education
 Employer's business
 Shopping
 Visiting friends or relatives
 Personal business (e.g. doctors, bank)
 Leisure/recreational (e.g. sports, cinema, restaurant)
 Giving someone a lift

Other, please specify

Q9 **FREQUENT:** What type of vehicle do you usually drive?
INFREQUENT: What type of vehicle were you driving?

- Car Van Motorcycle Lorry Other

M6 J8 - J10A in last 3 months

I am now going to ask you some questions relating to your journey. Please think only of this section and consider only the last 3 months.

Q10 In the last 3 months, since allowing drivers to use the hard shoulder, to what extent do you agree that...

	Agree strongly	Agree	Neither	Disagree	Disagree strongly
It is difficult to join the motorway from the slip road	<input type="checkbox"/>				
It is difficult to exit the motorway	<input type="checkbox"/>				
There is usually a queue of traffic on roads leading to the motorway	<input type="checkbox"/>				
There is usually a queue of traffic from main motorways to exit slipways	<input type="checkbox"/>				
Vehicles constantly cut lanes to take exit at junctions	<input type="checkbox"/>				

Q11 In the last 3 months specifically, how would you rate the level of congestion along this section?

- Stop start throughout Heavy but moving traffic
 Stop start in most places Clear and able to travel as fast as I like
 Stop start in certain places Don't remember

Q12 Where in particular have you experienced those stop start situations?

- M6 J8 M6 J9 M6 J10 M6 J10A Not sure

Using the Hard Shoulder

Q19 In the last 3 months, have you driven along this section when the hard shoulder has been in operation?

Yes Go to Q20 No Go to Q22

Q20 In those instances, did you actually drive in the hard shoulder itself?

Yes Go to Q21 No Go to Q22

Q21 How would you rate your experience of using the hard shoulder?

Very good Neither good nor poor Very poor
 Quite good Quite poor

GO TO Q23

Q22 Why not? PROBE FOR FULL ANSWER

Q23 What is your opinion of the hard shoulder running along this section? PROBE FOR FULL ANSWER

Q24 What would you say has been the MAIN benefit of hard shoulder running in the last 3 months? PROBE FOR FULL ANSWER

Q25 To what extent do you agree or disagree that allowing drivers to use the hard shoulder as an additional lane in this section has...

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Improved journey reliability (you are able to predict how long it will take)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Improved safety	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Improved traffic flow	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Encouraged drivers to use this section on a more regular basis	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Q26 Overall, do you think that allowing drivers to use the hard shoulder as an additional lane has made this section...

Better Same Worse

Q27 Overall, how would you compare this section to other motorway sections without hard shoulder running? This section with hard shoulder running is ...

Better Same Worse

Q28 Do you think that hard shoulder running should be extended to other motorways?

Yes, definitely Yes, maybe Definitely not

Through Junction Running

Q29 At M6 J10, you are now able to drive on the hard shoulder through the junction at all times if you are exiting at the next junction (SHOWCARD).

Were you aware that you could do that?

Yes No

Q30 Since its implementation, have you driven through that junction using the hard shoulder?

Yes Go to Q32 No Go to Q31

Q31 Why not? PROBE FOR FULL ANSWER

GO TO Q34

Q32 How would you rate your experience of driving through that section?

Very good Neither good nor poor Very poor
 Quite good Quite poor

Q33 To what extent do you agree that the signage for that specific junction is easy to understand?

Strongly agree Neither agree nor disagree Disagree strongly
 Agree Disagree

Q34 What is your opinion of this specific section where you can drive through the junction? PROBE FOR FULL ANSWER

Q35 To what extent do you agree or disagree that allowing drivers to drive through the junction has...

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Improved journey reliability (you are able to predict how long it will take)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discouraged drivers to cut lanes constantly	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Improved traffic flow	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Q36 Overall, do you think that allowing drivers to drive through the junction on the hard shoulder has made this section...

- Better Same Worse

About you

Q37 Gender

- Male Female

Q38 Which age category do you fall into?

- 17-24 25-34 35-44 45-59 60-64 65 +

Q39 Which of the following best describes your employment status?

- Full time employment Looking after family/home
 Part time employment Unemployed
 Retired from paid work Other
 Full time education

Q40 Which of these best describes your current/previous occupation if retired?

- Professional/managerial Skilled/manual
 Clerical/administrative Semi/unskilled manual

Q41 How would you describe your ethnicity?

- White British Asian or Asian British - Bangladeshi
 White Irish Any other Asian background
 Any other white background Black or Black British - Caribbean
 Mixed - white and black Caribbean Black or Black British - African
 Mixed - white and black African Any other Black background
 Mixed - White and Asian Chinese
 Any other mixed background Any other ethnic group
 Asian or Asian British - Indian Not stated
 Asian or Asian British - Pakistani

Q42 We would like to re-contact you for quality purposes only. If you are happy to be re-contacted, please provide us with your contact details below.

Name
Telephone number

Q43 I can confirm that this interview was conducted under the terms of the MRS Code of Conduct and is completely confidential.

Interviewer initials
Signature
Date

Location

- Corley Hopwood Hilton Park Tamworth Gallagher/ Ikea Town Centre

Appendix C: Analysis days for the video footage analysis

Table 42: Analysis days for the before case, M6 J10 Northbound

	Day-Type	Date	AM-Peak Time Period	PM-Peak Time Period
Merge	Sunday	02/08/2009	07:00 - 07:30	16:00 - 18:00
	Monday	03/08/2009	07:00 - 08:00	16:00 - 18:00
	Tuesday	04/08/2009	--	16:00 - 18:00
	Wednesday	05/08/2009	--	16:00 - 18:00
	Thursday	06/08/2009	08:00 - 09:00	16:00 - 18:00
	Friday	07/08/2009	08:00 - 10:00	16:00 - 18:00
Diverge	Saturday	08/08/2009	07:00 - 10:00	16:00 - 19:00
	Sunday	09/08/2009	07:00 - 10:00	16:00 - 19:00
	Monday	10/08/2009	07:00 - 10:00	16:00 - 19:00
	Tuesday	11/08/2009	07:00 - 10:00	16:00 - 19:00
	Wednesday	12/08/2009	07:00 - 10:00	16:00 - 19:00

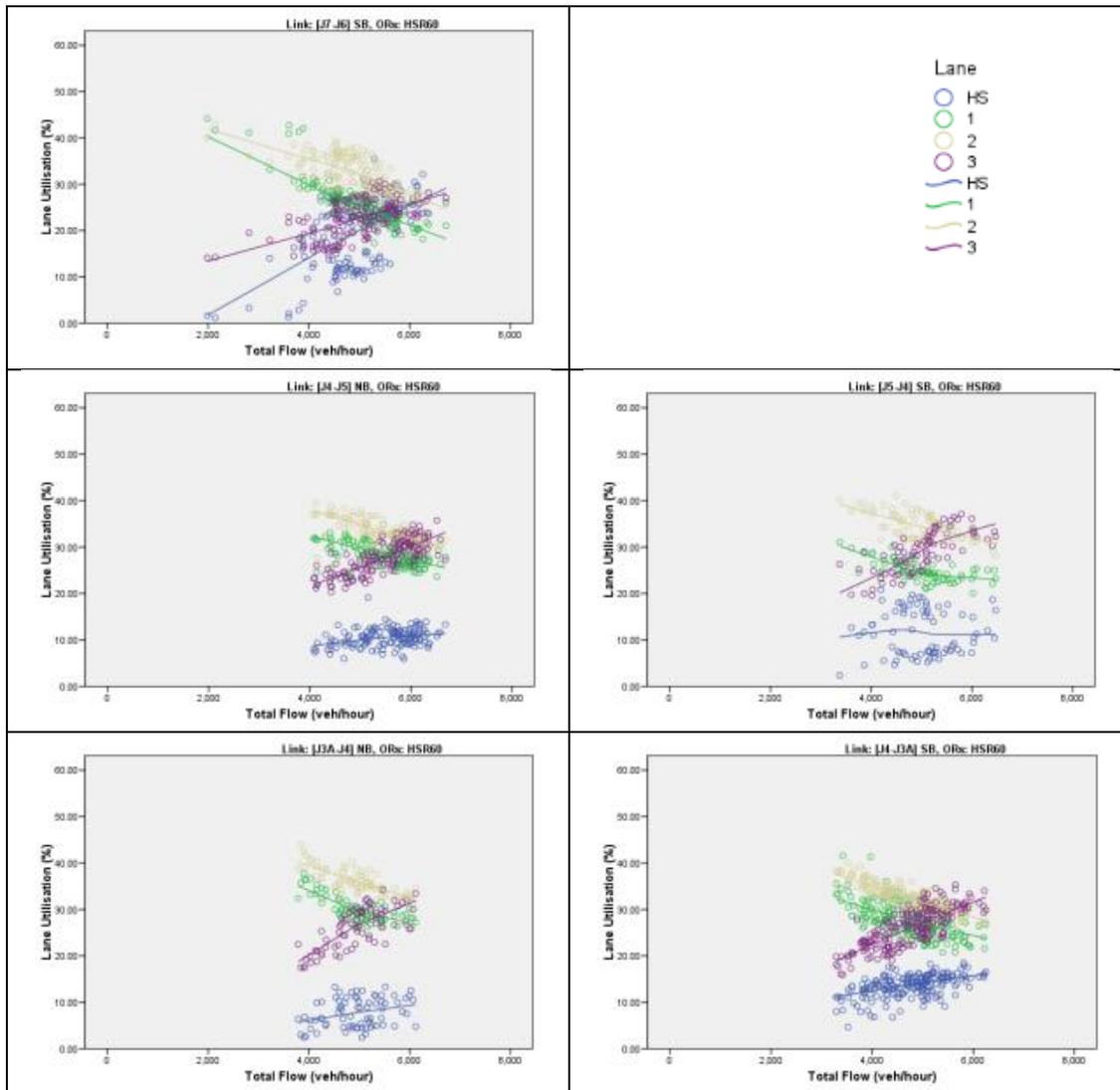
Table 43: Analysis days for the before case, M6 J10 Southbound

	Day-Type	Date	AM-Peak Time Period	PM-Peak Time Period
Merge	Saturday	08/08/2009	07:00 - 10:00	16:00 - 19:00
	Sunday	09/08/2009	07:00 - 10:00	16:00 - 19:00
	Monday	10/08/2009	07:00 - 10:00	16:00 - 19:00
	Tuesday	11/08/2009	07:00 - 10:00	16:00 - 19:00
	Wednesday	12/08/2009	07:00 - 10:00	16:00 - 19:00
Diverge	Sunday	02/08/2009	07:00 - 09:00	16:00 - 18:00
	Monday	03/08/2009	07:00 - 08:00	16:00 - 18:00
	Tuesday	04/08/2009	07:00 - 09:00	16:00 - 18:00
	Wednesday	05/08/2009	07:00 - 09:00	16:00 - 18:00
	Thursday	06/08/2009	07:00 - 09:00	16:00 - 18:00
	Friday	07/08/2009	07:00 - 09:00	16:00 - 18:00
	Saturday	08/08/2009	--	16:00 - 18:00

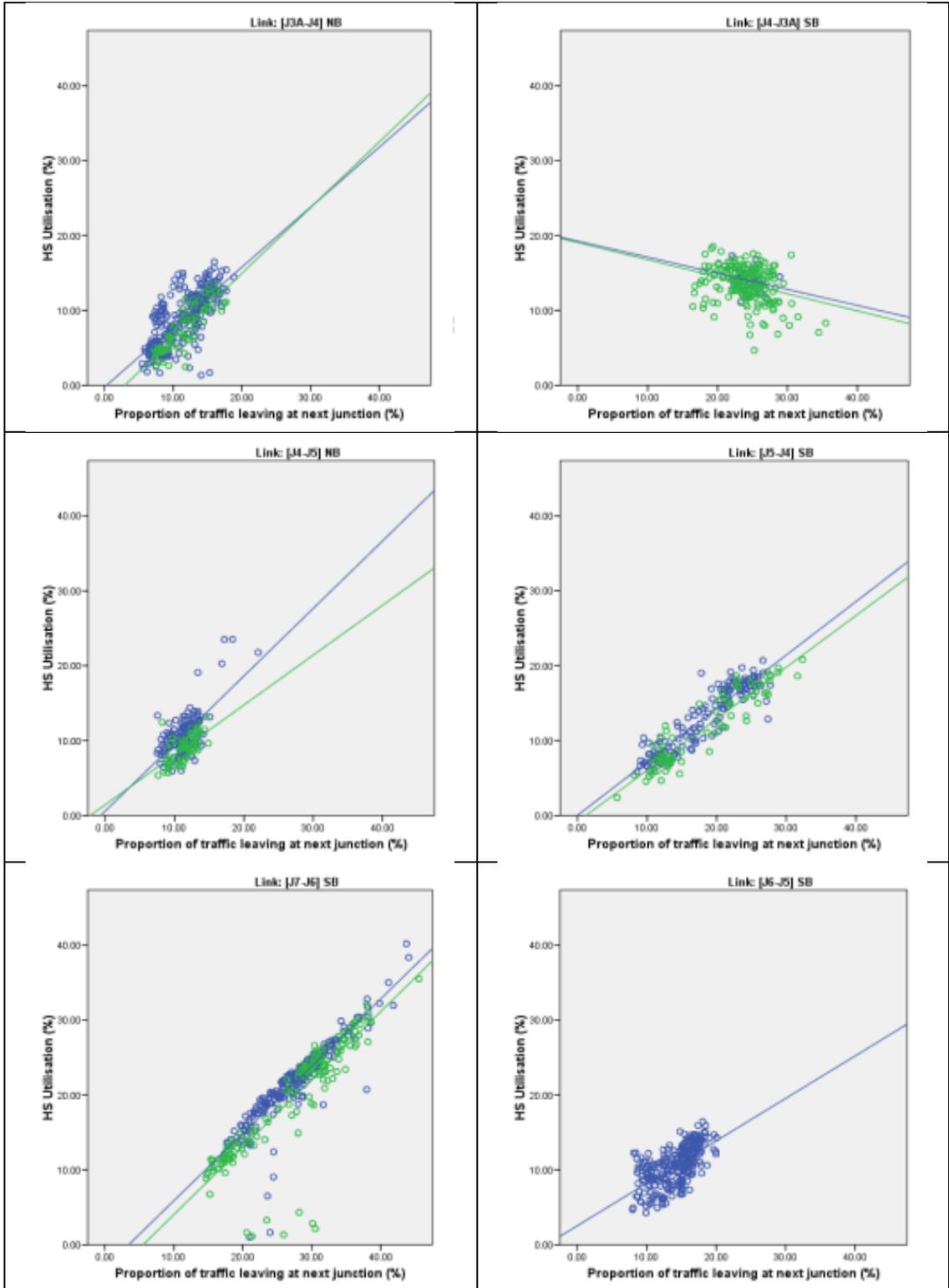
Table 44: Analysis days for the after case, M6 J10 Northbound

	Day-Type	Date	AM-Peak Time Period	PM-Peak Time Period
Diverge	Monday	28/11/2011	--	17:00 - 20:00
	Tuesday	29/11/2011	07:00 - 10:00	--
	Wednesday	30/11/2011	--	17:00 - 20:00
	Sunday	04/12/2011	07:00 - 10:00	17:00 - 20:00
	Monday	05/12/2011	07:00 - 09:00	17:00 - 20:00
Merge	Monday	30/01/2012	07:00 - 09:00	16:00 - 17:30
	Tuesday	31/01/2012	07:00 - 08:30	16:00 - 17:00
	Thursday	02/02/2012	07:00 - 10:00	16:00 - 20:00
	Friday	03/02/2012	07:00 - 10:00	16:00 - 20:00

Appendix D: Lane Utilisation during HSR operations



Appendix E: Hard shoulder utilisation vs proportion of traffic leaving at next junction



ORs
 ○ HSR50
 — HSR90