Evaluation of Variable Speed Limits: Empirical Evidence and Simulation Analysis of Stockholm's Motorway Control System

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To my beloved family
Abstract

Variable Speed Limits (VSL) are often used to improve traffic conditions on congested motorways. VSL can be implemented as mandatory or advisory. The objective of the thesis is to study in detail the effectiveness of VSL. The focus is on both, design parameters and conditions under which VSL are most effective. The MCS system on the E4 motorway in Stockholm is used as a case study.

The evaluation was conducted using empirical methods (including aggregate data from microwave sensors and other sources, and disaggregate data from a mobile study), and microscopic traffic simulation. The empirical analysis is based on before and after VSL data, including evaluation of individual measures of performance, and multivariate analysis in the form of the fundamental diagram, and speed-density relationships. The results from the empirical study are mixed with an indication that driver behavior has a strong impact on the effectiveness of the system.

The microscopic traffic simulation analysis included the development of a platform for testing VSL and more generally motorway control strategies. The simulation platform was calibrated and validated with the empirical data and includes in addition to VSL, and Automatic Incident Detection (AID) system, the ALINEA ramp metering algorithm. The test-platform allows the testing of different control strategies and various combinations of control strategies, under different scenarios and in a controlled environment. The results from the simulation study indicate that driver compliance is an important factor and VSL performance quickly deteriorates as compliance rate drops. Hence, VSL should be implemented as mandatory instead of advisory. In addition, mandatory VSL can be effective both, under incident and moderately congested conditions. A combined VSL and ramp metering strategy can be most effective in reducing travel time, improving traffic conditions on the motorway. Furthermore, the results indicate that such a strategy also has the least impact on the flows entering the motorway from the ramps.

Keywords: Motorway Control System, Mainline Control, Variable Speed Limits, Driver Behavior, Capacity, Intelligent Transport Systems, microsimulation model
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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

The Highway Capacity Manual (HCM, 2000), defines congestion in a major urban area as a situation when the traffic demand exceeds the bottleneck capacity downstream. Commuters driving in such a network are anticipating queue but do not know precisely when they will occur.

The rapid growth of motorization in combination with urbanization has resulted in higher traffic demand, which has in turn resulted in growing saturation of the road and motorway network. This has led to a great need for investments to increase network capacity and accessibility, a demand that is difficult to meet for financial, physical and ecological reasons in most major urban regions. Congestion problems demand the attention of transportation authorities to find solutions that ensure more efficient, safe and reliable traffic systems.

The road traffic system is a vital component of the infrastructure in both developed and developing nations, and has a substantial impact on the development of a country’s economy and socio-economic standard. The performance of a traffic system largely depends on the relationships between transport demand and supply (capacity, accessibility). Traffic performance is also heavily dependent on demand variability and the occurrence of traffic incidents, restricting the availability of road space. Motorway congestion has become a common phenomenon, especially during peak hours in major urban area.

On motorways, much of the variation in speed and headways between vehicles in the same lane and between lanes is characteristic of unstable traffic conditions. A minor incident may cause long traffic queues, congestion, and frustrated drivers, which in turn may lead to accidents and long travel times that entail a cost to society, the private sector, and individuals alike.

Smulders (1992) states that in situations of high demand and saturated conditions, drivers tend to stay in the fast (i.e. the left-most) lane as much as they can, leaving the other lanes under-occupied. The available road space is then under-used, with bunches of vehicles driving at high speed and with short headways in the fast lane. Lane change manoeuvres become difficult to undertake, creating disturbances and hazardous situations.

Continuous changes of traffic flow and speed characteristics over space and time result in dynamic conditions, leading to congestion and the build up and dispersal of queues. In this case, an Intelligent Transport System (ITS) is needed, that can consider varying demand over space and time. Considerable efforts have been focused on the development of strategies and systems for dynamic traffic management. A range of Intelligent Transport Systems (ITS) in vehicles (e.g. Advanced Travellers Information System (ATIS)) or integrated into the transportation infrastructure (e.g. Motorway Control System (MCS)), have been applied as countermeasures. ITS technology has contributed to new ways to manage and operate existing transportation infrastructures with the aim of increasing efficiency, reliability, safety and improving the environment without necessitating major physical changes in the road infrastructure.

Freeway management systems that use ITS include applications such as Entrance Ramp
Control, Exit Ramp Control, Mainline Control, Priority Control and Corridor Control aimed at increasing the capacity of the existing infrastructure through improved operating efficiency and fewer occurrences of congestion. Mainline control is used to control the traffic on motorway links in order to increase safety and motorway operation efficiency. These applications can include a decrease in and harmonization of heavy flow by warning drivers in advance of slow traffic, congestion, queuing ahead, or hazardous roadway conditions using one or a combination of the following systems. According to Papageorgiou (2003), mainline control may include one or a combination of the actions listed below:

- Driver information and guidance systems
- Variable speed limit signs (advisory or mandatory speed)
- Incident or congestion warning
- Mainline control
- Reversible lane control
- Keep-in-lane instructions
- Changeable message signs (lane closure, keep lane, congestion warning or environmental warning, work zone)

Mainline or link control by variable speed limitation can be defined as a system designed to regulate, notify and guide vehicles using the motorway mainline. Variable Speed Limit systems are frequently used to increase safety, reduce the risk of capacity breakdown caused by stop-and-go conditions by recommending travel speeds. These systems are typically implemented upstream of a known traffic bottleneck.

By forcing traffic to slow down in a controlled manner, congestion, shockwaves and flow breakdown can sometimes be avoided, allowing the traffic to maintain a homogeneous steady flow as its speed decreases. Typically, a motorway traffic management system includes detection of average speed, traffic volume, density, and environmental factors. Shockwave prediction algorithms and real-time information and guidance system, providing warning of road construction and maintenance activities, reduced visibility and slippery road surface conditions, are also used to support selection of appropriate driving speed.

The most common application of speed control appears to be for the purpose of queue warning. This can be achieved through Variable Speed Limits (VSL) showing recommended or forced speed upstream of a detected queue. These systems often comprise a number of possibilities in which main lane control can also be applied, including lane change and closed lane instructions triggered by accidents or road maintenance.

Studies have shown that compliance with displayed speed leads to less speed variance, more uniform headways, better utilization of all lanes and a stable or harmonized traffic flow resulting in improved safety, (Harbord, B., 1998). Queue warning systems may delay the onset of congestion and stop-start driving conditions, thus improving driving comfort and traffic safety. This also contributes to lower fuel consumption and emission reductions resulting from the lower frequency and severity of acceleration/deceleration manoeuvres.

The provision of real-time information is fundamental to any traffic control system. One important component in the Variable Speed Control loop is driver compliance and behaviour, which is difficult to detect, adding uncertainty to the problem of controlling motorway traffic. Driver behaviour models and resulting traffic impacts must be based on empirical studies; very few such studies however are reported in the literature. The thesis documented in this
report addresses this knowledge gap using the Motorway Control System (MCS) in Stockholm as a case study.

1.2 TRANSPORT POLICY

1.2.1 European transport policy

Transport is a key factor in a welfare state. Transport represents an important sector of the European economy, accounting for about 7% of GDP and more than 5% of total employment in the EU (European Communities, 2009). Transport is crucial to the EU’s economic competitiveness and commercial, economic, and cultural exchanges.

A demand for a rapid transportation and increasing numbers of vehicles attempting to use an infrastructure with limited capacity create congestion. Congestion leads to queuing and mounting delays and sometimes poor quality of service can challenge accessibility and safety, increase environmental pollution and by extension economic development. According to the White Paper on European Transport Policy, the external costs of road traffic congestion are estimated at 1% of the EU’s GDP. Urban transport accounts for 40% of CO2 emissions and 70% of emission of other pollutants arising from road transport. Europe’s road have become safer in recent years: the number of road accidents involving a personal injury fell be some 12% between 1991 and 2007 and the number of road fatalities dropped by more than 44% over the same period.

The EU needs an integrated transport system based on a fast, reliable, and safe infrastructure that serves the needs of businesses and individuals. The goal of the European Transport Policy is to establish a sustainable transport system that meets society’s economic, social and environmental needs and is conductive to an inclusive society and a fully integrated and competitive Europe. These properties are broken down into more operational goals as follows:

- Quality transport that is safe and secure.
- A well-maintained and fully integrated network.
- More environmentally sustainable transport.
- Keeping the EU at the forefront of transport services and technologies.
- Protecting and developing the human capital.
- Smart practice as traffic signals
- Planning with an eye to transport: improving accessibility.

The common policies include a rising demand for accessibility in a context of growing sustainability concerns, better integration of the different modes of transport as a way to improve the overall efficiency of the system and acceleration of development of innovative technologies.

1.2.1 The Swedish transport policy

The Swedish public road network consists of over 138,000 km of roads. In addition, there are 75,000 km of private roads with central government grants and an extensive network of private roads without government grants. The public road network accounts for most traffic.

The Swedish transportation system has contributed to a robust economy. In 2000, the transport sector contributed SEK 97 billion to Sweden’s GDP (almost 4.4%). The transport
sector employs some 200,000 people, or 7% of the country’s total work force in trade and industry, (Confederation of Swedish Enterprise /Svenskt Näringsliv, 2005).

In major Swedish cities, especially in Stockholm and Gothenburg, road traffic congestion causes problems, as is also the case in most major cities around the world. The road capacity of streets and roads during rush hour periods is quite simply inadequate. In Stockholm, the population is growing at a rate of some 20,000 people a year (Regional- and trafikkontoret 2007), leading to increase demand for mobility, and even greater pressure on city streets and roads. During rush hour the Stockholm traffic system comes close to reaching its maximum capacity. The traffic situation also causes environmental problems in the form of more noise (Miljöförvaltninggen 2006) and emissions (SLB-analys 2005). Traffic queues create irritation and cause delays that entail a cost to society. Congestion and traffic queues increase the accident risk and are also harmful to the environment.

Various countermeasures to increase the accessibility of major arterials have been suggested, including implementation of the Motorway Control System (MCS) in Stockholm, (Vägverket, 2003). Furthermore Stockholm introduced a congestion charging system in 2006 (Bardaran, S. et.al. 2008), which cut traffic in the city centre by 20% initially but the traffic situation is still congested along the E4 motorway passing through Stockholm to Arlanda (not included in the congestion charge area) where the MCS is implemented.

The Swedish transport policy is related to the EU’s transport policy. The Swedish Parliament adopted a transport policy, Government Bill 1997/98:56, called "Transport Policy for Sustainable Development", that includes one general and six specific objectives, (Regeringskansliet, 2003). In March 2009 the objective of the transport policy was reviewed and presented in a Government Bill. The objectives of the transport policy are to ensure the economically efficient and sustainable provision of transport services to people and businesses throughout the country (Näringsdepartemente, 2009). These objectives included both functional and impact objectives.

To achieve the functional objective (accessibility) and the impact objective (health, safety, and environment) the following was proposed:

- **Functional objectives (accessibility):** The design, function and use of the transport system will contribute to provide everyone with basic accessibility of good quality and functionality and to development capacity throughout the country. The transport system will be gender equal, meeting the transport needs of both women and men equally.

- **Impact objectives (health, safety, and environment):** The design, function and use of the transport system will be adapted to eliminate fatal and serious accidents. It will also contribute to the achievement of the environmental quality objective and better health conditions.

In achieving two the objectives ITS can play an important role. In recent decades, Europe has suffered from increasing levels of congestion in major urban regions. If this problem cannot be resolved through capacity expansion, which is becoming more and more difficult, it will hamper economic growth. Expanding the traffic network may be in conflict with most of the policy objectives listed above. These objectives call for using the available infrastructure more efficiently, safely and in a more environmentally friendly way. Recently, significant emphasis has been laid on the application of advanced information and communication technologies in transportation. Suitable Intelligent Transport Systems (ITS) can be
implemented alongside different traffic control measures to enable the infrastructure to be used more efficiently and more safely with less pollution.

1.3 THE SWEDISH ROAD ADMINISTRATION’S ROLE AND STRATEGY FOR ITS

The Swedish Road Administration is responsible for the administration and maintenance of state roads; the Swedish municipalities are responsible for municipal roads and streets. Each municipality can formulate municipal policy documents, such as road safety programmes, environmental programmes, etc. The Swedish Road Administration wants to create a common platform and uniform focus on ITS and has an aim to spread knowledge and interest in ITS out in the regions and municipalities. In order to formulate a common strategy for ITS, the Swedish Road Administration produced a “Detailed document on ITS” pointing out five ITS focus areas for ITS for the period 2008-2017:

1- More effective and sustainable commuting to work, which, from the perspective of the road authority means improved travel and traffic information services to increase accessibility to public transport and promote co-modal travel, where it is possible to switch between public transport and private travel, in areas that are attractive to commuters.

2- More effective and more sustainable freight transport. This primarily includes services for differentiated kilometre tax and information services for carriers.

3- Improved road safety from the perspective of the body maintaining the road. This principally includes services for greater compliance with the applicable speed limits.

4- Quality-assured traffic information concerns the road authority’s responsibility for ensuring more effective data collection and improved control systems for the provision of information.

5- Reliable and effective working practices concern the road authority’s role as a supplier of data and information.

1.4 INTELLIGENT TRANSPORT SYSTEMS ACTION PLAN

The European Commission (2008) took a major step towards the deployment and use of Intelligent Transport Systems (ITS) in road transport. An Action Plan was adopted, which suggests a number of targeted measures and a proposal for a Directive laying down the framework for their implementation. The Action Plan aims to accelerate and coordinate the development of Intelligent Transport Systems (ITS) in road transport, making the interfaces with other transport modes more environment-friendly, more efficient, safer and more secure.

The Action Plan outlines six priority areas for with area a set of specific actions and a clear timetable identified for each area. Finally the Action Plan will help to combine the resources and instruments available to deliver a sustainable added value for the European Union.

1.5 ITS AND POTENTIAL IMPACTS

Technological innovation is expected to be a major contributor to the solution of transport challenges. New technologies Intelligent Transport Systems (ITS) can be an effective countermeasure. The application of ITS technology assumes that it is possible to change the
way we manage and operate road transport systems and make them more efficient, more reliable, safe and environment-friendly without any physical changes.

The potential impact of ITS has been assessed both through research and in the early stages of deployment. Journey time reductions of up to 20% and increases in network capacity of 5-10% are reported to have been achieved in various combinations. Safety improvements have often been estimated at around 10-15% for certain specific types of accidents (rear-end collisions), and survival rates have also increased. Integrated strategies for pollution control and traffic limitation have led to initial estimates of reductions in ground-level emissions, (EC, White Paper on Transport Policy, 2001). The use of ITS is also strongly advocated in Sweden as a means of achieving the “VISION-ZERO” objective (SNRA, 1996). However scientific evidence to support his has yet to be presented.

1.6 DYNAMIC TRAFFIC MANAGEMENT ON MOTORWAYS

In the Freeway Management Handbook (1983) freeway management is defined as the “control, guidance and warning of traffic in order to improve the flow of people and goods on these access facilities” (Neudorff, L.G. et al., 2003). According to TRB (1994), this definition is expanded to cover any activity carried out to utilize a freeway facility in accordance with present aims and the objectives set for that facility. These objectives include those that deal with impacting and influencing the surrounding communities and jurisdictions.

Freeway traffic management and operation is the application of previously assigned policies, strategies, and technologies. Dynamic traffic management systems on motorway make use of functions such as incident management and dissemination of information to road-users. This will improve motorway system performance and efficiency by reducing the impacts and occurrence of recurring congestion, minimizing the duration and effects of non-recurrent congestion, hence guaranteeing safety, reducing travel time, energy consumption and pollution, and many other related aspects, (Klijnhoit, J.J., 1991). Road users’ experience of stress can be reduced by providing them with information about traffic conditions, in order to help them make the right decisions. A wide range of applications for motorway control management can be found in the literature, e.g. Daganzo, C.F. et al. (2002).

1.7 OBJECTIVES AND SCOPE

The objective of this thesis is as following:

- Estimate in detail the impacts of advisory Variable Speed Limits (VSL) system using on E4 motorway in Stockholm.

- Analyze the sensitivity of the effectiveness of VSL to design parameters (mandatory vs. advisory) and driver behavior

- Assess the effectiveness of combined motorway control with, Variable Speed Limits (VSL) and Ramp metering.
1.8 RESEARCH FRAMEWORK

Behavior when driver are faced with advisory speed limits is of fundamental importance for the effectiveness of VSL. Since VSL messages are triggered by the occurrence of random traffic incidents it is difficult to carry out controlled before and after experiments of VSL impacts in real life traffic. The following research framework was therefore applied:

- Field studies of driver behaviour and traffic impacts with and without VSL application
- Development, calibration and validation of a simulation model based on the empirical studies.
- Use of the simulation model for controlled experiments of traffic performance impacts with and without VSL.
- Use of the simulation model for controlled experiments of traffic performance impacts with and without application of other control strategies, VSL and ramp metering.

1.9 STRUCTURE OF THE THESIS

The thesis is structured as follows: Chapter 2 contains a review of existing literature on evaluation of VSL and ramp metering with an associated discussion, Chapter 3 describes the Motorway Control System implemented on the E4 motorway in Stockholm. Chapter 4 presents the methodology applied in a related case study, Chapter 5 describes a field study to evaluate of the impacts based on before and after data of individual traffic characteristics based on a simple measure of performance. The field study included also another study for evaluation of VSL impacts on the relationship between speed and density important variables. Chapter 6 presents a mobile study for the evaluation of the impacts of VSL traffic performance.

Chapter 7 includes a simulation-based analysis to test the impact of VSL with the assumption of different levels of compliance. In the same chapter, the microsimulation model is applied to test the impact of VSL to resolve recurrent and non-recurrent congestion. In Chapter 8, different control strategies are applied, including ramp metering, to test the impact of ramp metering to study the motorway’s traffic performance. In the same chapter, the combination of both VSL and ramp metering management and their impacts on traffic performance along the motorway are tested. Finally, in chapter 9, the findings are presented, conclusions drawn and directions for further research are identified.
CHAPTER 2 LITERATURE REVIEW

In this chapter an overview of the existing forms of traffic managements that intended to improve traffic flow on motorways. These involve the application by suitable Intelligent Transport systems (ITS) of different traffic control measures. In this study, a particular form of traffic management that uses Variable Speed Limits (VSL) in response to prevailing traffic conditions and ramp metering will be reviewed. The focus is on the function, fields and evaluation through simulation of the impact of the VSL, ramp metering and the two combined.

To better understand the reasons behind the various approaches to motorway control we here introduce basic concept of traffic flow theory.

2.1 BASIC THEORY OF TRAFFIC FLOW

In the previous chapter different types of ITS were described with main focus on the Mainline control by Variable Speed Limits (VSL) as well as its appropriate uses. The nature of operating this system is related to the characteristics of the motorway facility. Motorway facilities are composed of connected segments consisting of basic motorway segments, ramp segments and weaving segments. When several of these segments occur in sequence, they form a motorway facility (TRB, 2000). The demand for free traffic flow with high-speed movement on limited access facilities and without the annoyance of flow interruptions from traffic lights was the reason that motorways were designed. Growth in transport demand leads to increasingly severe congestion, both recurrent and non-recurrent, that will increase delay, travel time and stress, which in their turn may lead to accidents and undesirable impacts on the environment.

Traffic flow theory attempts to model the relationship between speed, flow, density and other variables. Theoretical development has been conducted since the 1930s to describe mathematically the interaction between vehicles, drivers, and the infrastructure in different traffic flow theories by Greenshields (1935), Greenberg (1959), and Edie (1961) and others. Different models were developed and utilized to plan, design and operate of transport facilities.

Traffic flow theory can be explained in a macro perspective using theories from hydrodynamics. Each vehicle on the road is assumed to behave like a water molecule travelling in a pipe. At low flow, “Laminar flow” condition occurs, i.e. the molecules/cars travel in an orderly fashion at more or less constant speed. When conditions approach capacity, the molecules behave in a turbulent way, causing large variance in speed/flow observations and a general reduction in capacity, [Bang, 2005]. Figure 2.1 below illustrates these phenomena using real traffic data obtained within the current project for three lanes of the E4 motorway bottleneck in Stockholm.
Traffic flow can be classified as interrupted if the flow is regulated by external means, such as a traffic signal, or uninterrupted, e.g. a motorway facility where the flow is mainly regulated by vehicle-vehicle and vehicle-roadway interactions. In interrupted flow, these interactions play a secondary role in defining traffic performance. The most common terms used to describe traffic flow phenomena are speed (v), traffic flow (q), density (k) and time headway (h). Traffic flow, speed and time headway between vehicles are important characteristics that affect safety, level of service, driver behaviour, and capacity in transportation systems.

The variables q, k, and v are stochastic and mutually dependent. The fundamental relationship of macroscopic traffic stream characteristics between flow, density, and speed in an uninterrupted flow conditions can be expressed as:

\[ q = k \times \bar{v} \]

where
- \( q \) = traffic flow (v/h)
- \( k \) = density (v/km)
- \( \bar{v} \) = space-mean speed (km/h)

When density is low, drivers travel at high speeds (free flow) and do not experience interaction with other vehicles. When density increases, traffic comes to a complete standstill in a queue at maximum density (called jam density).

Traffic stream models including single- and multiregime models have been developed to describe the state behaviour of a traffic stream; a detailed overview of traffic stream models can be found in (May, A. D., 1990).

The first single-regime model was developed for uninterrupted traffic flow by Greenshields (1935). Greenshields assumed that speed and density are linearly related, since the relationship between speed \( V_f \) and density \( K_f \) are constant, see figure 2.2.
\[ v_{(k)} = v_f \left(1 - \frac{k}{k_j}\right) \]  

(Linear model)  

(1)

Where:
- \( v \) = mean speed (space-mean speed) (km/h)
- \( v_f \) = free flow (km/h)
- \( k \) = density (v/km)
- \( k_j \) = jam density, the maximum possible value for density

\[ 0 = \ln \left(\frac{k}{k_j}\right) \]

where; \( v_0 \) is optimal speed at maximum flow (capacity).

The model shows a good correlation between the model and field data in figure 2.3, which displays an S-shaped relationship.

Figure 2.2. Flow, Density and Speed relationships, (TRB, 2000).
All these models were developed to mathematically interpret the relationship between speed, density, and traffic flow. Of interest here is that these models were applied on field data and the results showed a deficiency in reliably tracking the measured field data near capacity, (May, A. D., 1990), which led to multi-regime models being proposed by (Edie, L. C., 1961), to achieve better adjustment of models to field data. Multi-regime models imply applying different models for different regimes. However, a difficulty arises in applying the latter model with regard to determining the breakpoint between regimes.

2.1.1 Traffic breakdown and traffic congestion.

Motorway breakdown have become a common phenomenon, especially during peak traffic hours. Congestion can be analysed using the fundamental relationship between traffic flow \( q_A \), density \( k_A \), and speed \( v_A \). The relationship between density \( k_A \) (number of cars per road segment) and traffic flow \( q_A \) (number of cars passing a road section per unit of time) create the shape in figure 2.4.

![Fundamental diagram representing traffic behaviour on a homogenous motorway, (Hegyi, A., 2004)](image)
This figure represents traffic behaviour on a motorway, showing the maximum traffic flow, which is the capacity, while the density corresponding to the capacity is called critical density.

The area created under the curve is divided into two regions. The region with density less than the critical density represents uncongested conditions and the area with density higher than the critical density represents the congested conditions. Continuous increases in density reduce traffic flow leading to a condition of unstable traffic flow and condition of jam density at which traffic comes to a complete stop. Motorways can be best utilized during critical density when traffic flow has reached capacity.

Instability causes vehicles to slow down (brake) and experience frequent stop-and-go situations. After a while, the queue that has built up gradually dissolves, mostly without the drivers knowing why he or she was queuing. Incidents, e.g. traffic accidents, crashes, or wrecks, or road maintenance cause reductions in road capacity. Consequently, delays and secondary incidents may occur.

Smulders (1992) describes unstable traffic flow as follows; drivers tend to stay in the fast, i.e. the left most, lanes as much as they can, leaving the other lanes under-occupied. The available road space is therefore used inefficiently and in the fast lane bunches of vehicles develop, driving at high speed and with short headways. Maneuvering in lane changes becomes very difficult and within these bunches of vehicles the disturbance created by such manoeuvres is seriously intensified. However, the overreaction of the drivers to deceleration of their predecessors is the reason behind the intensification. These will result in shockwaves, which in turn lead to congestion, and, in the worst scenario, accidents.

According to Papageorgiou (1983), two types of congestion can be classified: recurrent (occurs daily during rush hours) and non-recurrent (due to incidents). The former type occurs during morning and evening rush hours, while the latter occurs, for instance, as a result of accidents. Both types of congestion propagate from downstream to upstream, and while recurring congestion clears upstream first, the opposite is true for non-recurring congestion (Graves, T. L. et al., 1998). Results from the same study also indicate that non-recurrent congestion propagates more rapidly than recurrent congestion.

The difference between the two types of congestion is that recurrent congestion is easy to predict while non-recurrent congestion occurs randomly. This is the reason why it is difficult to adopt a proper control strategy to prevent the occurrence of non-recurrent congestion or traffic breakdown.

Traffic congestion is becoming more serious in many areas leading to excessive delays and unstable traffic flows on motorways, with severe consequences in terms of safety and environment. Motorway Control System (MCS) in the form of dynamic traffic management and control systems have been developed and implemented to deal with congestion. Examples of strategies (mentioned earlier in chapter 1) include Mainline Control (Lane Control), ramp metering, Variable Speed Limits (VSL), and others. Motorway traffic management is generally based on estimation of traffic conditions that are based on data concerning characteristics such as speeds and traffic flows collected in real time. These data are used as the basis for control as well as for traffic information to road users. Drivers adjust their speeds in order to better respond to changing traffic conditions downstream due to lane closures,
reduced visibility, slippery road surface, work zones, etc. In such cases VSL systems for example, display successively decreasing speed limits upstream of a bottleneck.

The basic idea of the applying dynamic control is based on the fundamental relationship between the macroscopic traffic stream characteristics, flow (q), density (k), and speed (v), with reservation that this relationship varies from day to day without any reason. When the relationship between traffic characteristics for the studied road segment has been determined the next step is to determine under what conditions the VSL will be applied.

Two views on the use of dynamic speed limits had gained prominence in Hegyi (2004). The first emphasizes the homogenization effect and the second focused on preventing traffic breakdown by reducing the flow by means of speed limits.

Under a flow homogenization strategy, the applied VSL is usually above the critical speed (speed that corresponds to the maximum flow). There are indications that the application of VSL is useful at volumes 15-20% below capacity, (Smulders, S., 1990). These speeds do not limit the traffic flow but only slightly reduce the speed and/or density differences, thereby producing a safer and more stable traffic flow. No significant improvement in traffic flow efficiency was measured (Van den Hoogen and S. Smulders, 1994). In theory this approach can increase the time to breakdown (S. Smulders, 1990), but it cannot suppress or resolve shock waves.

The traffic breakdown prevention or shockwave eliminating strategy Hegyi (2004) allows speed limits that are lower than the critical speed in order to limit the inflow to bottleneck areas. To suppress shock waves by applying speed limits upstream of a congested segment, the inflow to the jammed area is reduced. This in its turn will lead to a situation there the inflow to the jammed area is smaller than its outflow, which gradually balances (compensate for) the previous high density, thereby dissolving the congestion.

Other studies investigate the fundamental diagram (curve) for two cases with and without VSL with a focus on the point of intersection of the two curves. Zackor (1991) suggests that the two curves intersect at a point close to the critical occupancy, see figure 2.5 a. This point lies at an increasing occupancy for decreased VSL, while Hegyi (2004) states that the two curves meet but do not actually intersect, 2.5 b.

![Figure 2.5. VSL impact on flow –occupancy; (a) (Zackor 1991) and (b) Hegyi (2004).](image-url)
On conclusion that can be drawn from the above is that it can be shown that activation of VSL at occupancies lower than the point of intersection of the VSL and non-VSL flow occupancy diagram will decrease traffic flow efficiency and increase travel time. While the case of activation of the VSL at the cross point occupancies will improve traffic flow stability and improve traffic flow due to later occurrence of congestion. The question is which is the most efficient switching of the VSL.

Control strategies for VSL switching are usually based on real-time decisions compared to pre-selected thresholds of traffic flow, mean speed or occupancy. As these characteristics vary due to traffic composition, traffic condition or weather condition etc, different thresholds for different sites, different road segment and different stochastic conditions must be calibrated. Current implemented thresholds are chosen in an ad hoc way which does not necessarily utilize the potential impact of the VSL on traffic flow efficiency (Papageorgio, M. et. al., 2008).

Papageorgio (2008) proposed a new approach of slope-based decision. He employed a slope estimator for the flow-occupancy diagram and uses the slope estimation to produce critical occupancy estimates. As the real traffic flow approaches the critical occupancy area, the slope of the flow-occupancy diagram will approach zero, regardless of site or prevailing conditions. The reason for using this method is that specification of the thresholds for the slope is easier and more general than the specification of thresholds for absolute values of the flow variables. What is more, this procedure does not require threshold calibration for different sites. Results from this study shows that the -point of intersection is found to lie on or slightly beyond the non VSL critical occupancy. The VSL-affected flow-occupancy curves intersect crosses the non-VSL curve, shifting the critical occupancy to higher values.

Messmer et al. (1994) suggest that the impact of link control has to be well understood in order to optimize the design of such systems. The literature on evaluation of VSL systems is also rather limited, both from the point of view of methods for the evaluation of such systems, and empirical evidence and systematic analyses regarding their effectiveness.

### 2.2 OVERVIEW OF TRAFFIC CONTROL STRATEGIES ON MOTORWAYS

The aim of applying traffic control management on motorways is to better utilize the motorways as transport systems to ensure safe conditions for drivers. Papageorgiou M. (1983) divided the control measures into two types;

- Control measures affecting the fundamental diagram. Avoid congestion by maintaining lower speed upstream the congested area, which can be performed by applying the Variable Speed Limits.

- Control measures affecting density. Avoid congestion by maintaining density below critical density. This can be performed either by metering traffic flow or by diverting traffic upstream of the congested segment.
2.2.1 The concept of lane control

Lane control includes different types of traffic control applications on segments between interchanges are typically employed on motorways. Lane Control includes Variable Message Signs (VMS) such as keep in lane, closed lane and lane change instructions when accidents occur or road maintenance is being carried out. VMS can also be used to warn drivers of adverse weather conditions such as slippery road surfaces (Allogg, AB, 2002; Pirkko, R., 2001), fog (Cooper, B.R. et al., 1993; Hogema, J.H. et al., 1997), wet road conditions and darkness (Zackor, H., 1979), or road maintenance being carried out, “work zones” (Lin, P. W. et al., 2004; Ober-Sudermeier, A., Zackor, H., 2001). Another type of mainline control is to apply Variable Speed Limits (VSL) that vary speed to hold drivers adapt their speed upstream of downstream queues (Smulders, S., 1990, 1992, 1996; Smulders, S. and Helleman, D.E., 1998) or to match traffic, environmental and weather conditions (Pirkko, R., 2001) and reduce fuel consumption and emissions on freeways (Tonkelaar 1994).

Motorway traffic control measures are commonly applied strategies. Motorway traffic control systems have been in use in the United States since 1960 on the New Jersey Turnpike, and since 1962 in Detroit, where a system was implemented on the John C. Lodge Freeway. A selection of these measures have been installed on motorways in many metropolitan areas in Europe since the 1970s (Germany, the Netherlands, and France), and since the 1990s in Britain, Sweden, and Australia. General reviews of practical Variable Speed Limit Systems can be found in (Robinson, M., 2000; Wilkie, J. K., 1997; Papageorgiou, M. et al., 2003).

Lane control aims to utilize existing infrastructure more safely and efficiently by controlling traffic on the motorway mainline itself. A wide range of Lane control applications have been employed on freeways in Germany, the Netherlands, and France for some time and more recently in the United Kingdom and Sweden.

Motorway Control Systems are in general based on open loop or closed feedback loop strategies. Closed loop control is complex and dynamic, and depends on the interaction of all the components in the system, see also figure 2.6. The communication network for MCS is vital to the operation of the system and must be reliable. The most used control strategy to deal with both recurrent and non-recurrent congestion is the closed loop, which is assumed to be more reliable. The open loop strategy requires previously collected data to select the best alternative for accessibility. Traffic data such as average speed, traffic volume, and density are collected to determine appropriate speeds at which drivers should be travelling.

![Figure 2.6. Framework for Lane Control, (Smulders, S. et al., 1998).](image-url)
One important component used in surveillance and control management is Automatic Incident Detection AID. This component is of critical importance in dealing with random incidents occurring on motorways. AID often relies on algorithms to detect incidents using data collected from, for example, inductive loops or microwave detectors. These algorithms are considered to be key components of a successful motorway traffic management system. The performance of the algorithm is dependent on the quality of the data collected.

2.2.2 Traffic detection

Many different types of detector have been utilized in traffic control management systems, e.g. inductive loop detectors, microwave detectors, radar, and CCTV cameras. The detectors register vehicle movements such as vehicle or vehicle axle passage time and speed. These observations can be used to calculate traffic parameters such as traffic flow, average speed, headway, acceleration and occupancy and other functions of these parameters. Detector data can also be processed to provide vehicle classification, delay, density, and other measures of effectiveness.

The most widely used technology to detect traffic is inductive loops, which are cheap to install. Other types of detection technology have also been introduced in recent decades, e.g. microwave detection. Inductive loop detectors, microwave detectors or video detection cameras are installed at regular intervals in each lane along the freeway. Winter maintenance and road surface wear from studded tyres in the Scandinavian countries often damage inductive loops, which was one of the reasons why all the inductive loops in the MCS on the E4 in Stockholm were replaced by microwave detectors in 2004.

The Dutch Motorway Control and Signalling System uses inductive loop detector stations, which are spaced approximately 500 m apart and measure one-minute averages of speed and volume across all lanes for AID and the system control algorithm.

In the M25 system in London, data is collected by inductive loops placed at 500 m intervals and through CCTV. The data collected comprises traffic volume, speed, headway, and occupancy. The strategy applied for selecting the decision of the speed depends on the traffic volume as the important factor for hourly mean speed variation.

2.2.3 Variable Speed Limits (VSL)

Variable Speed Limit (VSL) systems are an important motorway control strategy. They are used to help/require drivers to adjust their speeds in order to better respond to changing traffic conditions downstream due to lane closures, reduced visibility, slippery road surface, developing queues, etc. In such cases VSL systems for example, display successively decreasing speed signs upstream of a bottleneck. VSL has also been used on motorways to warn drivers to adjust their speeds because of adverse weather conditions, wet road surface, darkness (Zackor, H. 1979), and work zones (Lin, P. et. al., 2004) and (Ober-Sudermeier, A. and Zackor, H., 2001).

In general, VSL systems can be implemented as advisory, e.g. like the system in Stockholm and the VSL system implemented on a two-lane German motorway (Robinson, M., 2000), or mandatory (enforced) like the M25 Controlled Motorway round London (Wilkie, J. K., 1997). The latter method results in a more stable traffic flow since drivers respond to and accept the system better (Messmer, A. and M. Papageorgiou, M., 1994), (Kotsialos, A. and M.
Studies indicate that enforcement is necessary to achieve and maintain a sufficient level of acceptance. Various studies in the Netherlands for example, suggest that speed limits were not necessarily obeyed by drivers, most likely because the displayed speed signals were not mandatory but advisory (Messmer, A. and Papageorgiou, M., 1994).

VSL offers a possibility to improve the capacity of the freeway network (Keller, H, 1994), by forcing traffic to slow down in a controlled manner; VSL has the potential to reduce congestion, shockwaves and flow breakdowns on freeway networks and may dramatically improve the efficiency of the infrastructure in terms of traffic flow throughput and total time spent. In order to achieve this, most of the applied VSL systems employ an algorithm based on some threshold values e.g. traffic flow, occupancy, mean speed or a combination of them. This threshold is used as the basis for deciding whether a specific speed limit should be switched on or off. The algorithms are location-dependent and often require fine-tuning.

**2.2.4 Automatic Incident Detection (AID)**

A traffic incident may be described as: an “abnormal and unplanned situation, including incident, adversely affecting the traffic flow”, (Appel, K. et al., 2002). It may also be described as “an event, which causes a need for assistance of involved drivers and /or warning of oncoming traffic in order to maintain safe driving conditions” (Bang, 1979). Since this definition includes a wide range of events, identification and classification of incidents are needed for the purposes of the operating system in order to distinguish between true and false alarms.

Graves et al. (1998) consider the time dimension as an important distinction between freeway breakdown prediction problems and automatic incident detection. Incident detection algorithms are reactive, while the freeway breakdown prediction algorithm attempts to anticipate the occurrence of congestion in the near future.

Automatic Incident Detection (AID), used in the surveillance and control management applied on motorways, is a critical element in dealing with random incidents that occur on motorways. AID often relies on algorithms to detect incidents, using data collected from, for example, inductive loops or microwave detectors. These algorithms are considered key components of a successful motorway traffic management system. The performance of the algorithm is dependent on the quality of the data collected.

Recognizing unusual patterns of traffic from normal conditions (comparing traffic parameters to pre-determined thresholds); the algorithm triggers an alarm when the thresholds are exceeded. This alarm is utilized through VSL to warn traffic running into a queue or slow-moving vehicles by slowing it down with speed recommendations.

The AID algorithm processes the collected data to analyze whether an incident has taken place or not. Improvements in detection rate and reduction of the number of false alarms are desirable for good performance of a motorway network.

AID algorithms are classified in two categories according to their decision-making process, which can be threshold based or dynamic traffic prediction based, (Zifeng, Jiang, 1998).
Other AID algorithms are the McMaster algorithm, the Minnesota algorithm, the APID and PATREG algorithms and the HIOCC algorithm (Agency, Highways, 2004). Dynamic traffic prediction algorithms often use a filter algorithm, e.g. the Kalman filter and the extended Kalman filter (EKF), (Constantinos, A. et al., 2006) to smooth the input signals. Although this is time consuming, it can reflect dynamic traffic flow processes and confirm incidents more precisely. Other types of algorithm include exponential-smoothing algorithms, dynamic multi-model algorithms, and the Bayesian algorithm. For more details, see (Zifeng, J., 1998).

Over the last forty years, five basic types of computer-based detecting algorithms for detecting incidents have been developed, (Zifeng, J., 1998):

- Comparative or Pattern Recognition Algorithms
- Statistical Algorithms
- Time Series and Smoothing/Filtering Algorithms
- Traffic Model and Theoretical Algorithms
- Advanced Incident Detection Algorithms

**Comparative or Pattern Recognition Algorithms**

This type of algorithm is a threshold-based algorithm, one example of which is the widely used California algorithm developed by Payne and Tignor (1978) as described below. It is based on the principle that an accident is likely to significantly increase occupancy upstream and reduce occupancy downstream. The average values of headway and occupancy are compared with the same values shifted in time and position. When the differences are beyond certain limits, the systems will signal an “incident alarm.” The averaging causes a delay in system response, which is a disadvantage. Lowering the limits in the decision process leads to faster decisions, but increases the proportion of false alarms.

**Occupancy models**

The California model is based on three occupancy features:

Absolute difference of occupancy ($O$) between upstream ($i$) and downstream ($i+1$) detector

![Diagram](image)

*Figure 2.7. AID based on comparison of traffic characteristics over time and space.*

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The difference in occupancy between upstream and downstream stations is analyzed, using for example inductive loops (upstream and downstream) in each lane to consciously register occupancy $O$ for even interval $n$ for each detector station $i, i+1$, etc…

Occupancy in time and space is then compared according to the following:

Comparison in space:

$$D_S = \frac{O_{n,i} - O_{n,i+1}}{O_{n,i}}$$

Comparison in time:

$$D_t = \frac{O_{n,i} - O_{n-1,i}}{O_{n-1,i}}$$

where

$O_{n,i}$ = occupancy at time $n$ minute and detector station $i$.

$O_{n,i+1}$ = occupancy at time $n$ minute and detector station $i+1$ etc..

**Statistical Algorithms**

Standard statistical techniques are used to determine whether observed detector data significantly differs from historical predicted values. An example of this type of algorithm is the Bayesian Algorithm, (Brydia, R. E.et.al., 2005). For this type of algorithm, data from normal traffic condition are used to develop mean and expected values for traffic conditions. Fluctuation variance in traffic pattern is taken into account by using confidence interval comparisons of real-time detection data and the typical values are used to determine whether they subside the normal range of data. An example of this type of algorithm is the Standard Normal Deviate (SND). This algorithm continuously compares average occupancy calculated over one minute to historically based values and SND.

**Time Series and Smoothing/Filtering Algorithms**

In smoothing/filtering algorithms, standard statistical techniques are used to determine whether observed detector data significantly differs from predicted values. There are a range of algorithms. The High Occupancy Algorithm (HIOCC), (Martin, P.T., 2001), developed at the British Transport Research laboratory, is one example. This algorithm inspects occupancy data from individual loop detectors for the presence of stationary or slow moving vehicles. A computer scans the detector occupancy data every tenth of a second and several consecutive values of instantaneous occupancy are examined to see whether they exceed algorithm thresholds. This algorithm is used in Britain on the M25 motorway (UK Highway Agency, 2004). The algorithms in this category use techniques to smooth or filter the data to remove minor fluctuations in detected data and then examine the data to see if they exceed algorithm thresholds.

**Traffic Model and Theoretical Algorithms**

Complex traffic flow theories and computer simulations are used in this type of algorithm to describe and predict traffic behaviour during incident detection. The detected actual traffic parameters are then compared to those predicted by the model. An example of this type of algorithm is the Catastrophe Theory, the McMaster Algorithm, developed in Canada. Catastrophe Theory takes its name from the sudden discrete changes that occur in one variable of interest, e.g. speed, while other related variables (traffic flow and occupancy) exhibit smooth and continuous change (Persaud et al., Hall, 1989). In this case, the Catastrophe Theory can distinguish between incidents that occur suddenly and queues that build relatively slowly.
**Advanced Incident Detection Algorithms**

An example of this type of algorithm is the Logit-based algorithm. This algorithm attempts to recognize incident patterns by using incident indexes, which represent the probability of occurring incidents. Distribution curves of traffic variables for normal and incident condition are compared. When the probability of incident occurrence is greater than for the normal condition, then incidents are reported in the algorithm.

**The performance of Automatic Incident Detection (AID)**

An important goal of motorway traffic management is the rapid detection of incidents and the management of traffic during incident conditions. The performance of an AID algorithm can be evaluated by testing the detection rate, time to detection, and the false alarm rate (Brydia, R.E. et al., 2005).

Detection Rate (DR), given as a percentage, is the ratio of the number of detected incidents to the actual number of incident in the data set. This often depends on how an incident is defined.

Detection Time (DT) is the difference between the time the incident was detected by the algorithm and the actual time the incident occurred.

False Alarm Rate (FAR) is expressed as a percentage per section. It can be defined as the ratio of incorrect detections to the total number of algorithm applications.

These parameters are not independent, see figure 2.8. For most algorithms, especially the comparative incident detection algorithms, the detection rate is proportional to the detection time, while the false alarm rate generally tends to be inversely proportional to the detection time.

![Figure 2.8: General relationship between DR-DT-FAR (Brydia, R.E. et al., 2005).](image)

The objective of implementing AID is to minimize the detection times (Brydia, R.E. et al., 2005). As the algorithm thresholds are adjusted to detect less severe incidents more quickly, minor fluctuations in traffic demand can cause the false alarm rate to rise, which is a problem.
In many of the incident detection algorithms, there is a trade-off between detection rate, detection time, and false alarm rate.

An evaluation study made by (Al-Deek, M. H., 1999) shows that the California algorithm had the most consistent performance. New advanced algorithms used in neural networks are potentially better but require significant calibration.

2.3 RAMP METERING

Ramp can be defined as an exclusive connection between two highway facilities consisting of a stretch of roadway of sufficient length to guarantee a safe merge manoeuvre of vehicles from on ramp with the main facility. The manoeuvre will create uncertain situations with increasing demand of vehicles at the on-ramp to gain access to a busy motorway. The unsafe manoeuvre creates incidents, which reduce the average speed, increase speed variation and thereby create queues upstream of the merge area.

Ramp Metering Strategies were developed to control the increased demand at the on-ramp by limiting the number of vehicles entering the main stream. It is the most direct and efficient way to control and upgrade freeway traffic (Papageorgiou, M. et al., 2003). Application of ramp metering can result in an increase in mainline throughput, and utilization of motorway capacity, reduce both the duration and extent of recurrent congestion and increase traffic safety through less congestion and safer merging. Ramp Metering is a common motorway management technique and uses signals located at the on-ramp to control and limit the number of vehicles entering onto the motorway from the on-ramp.

Application of ramp metering can be achieved by activating traffic lights based on pre-defined or variable signal cycle at the on-ramp merge point to allow vehicles to enter the motorway. Ramp metering can be used in two different modes: spreading mode, which endeavours to reduce the probability of a breakdown caused by a platoon of vehicles arriving from the on-ramp, and restricting mode, which aims at preventing a traffic breakdown and creation of congestion by preventing demands that exceed motorway capacity. The motorway can thus maintain its optimal operation, by regulating the motorways demand to be under its capacity. The inflow rate is determined by the proportion of green time given to the ramp signal. A rate of one or two vehicles per green may be allowed. In this way the traffic volume can be maintained at a selected level below capacity, and the turbulence caused at on-ramp merge areas where slower moving vehicles try to enter the faster moving traffic stream will be reduced (Bolenberger, K. and May, A, 1999). A stable flow conditions can thus be maintained and the average speed along the motorway will increase, which in turn both increases throughput in the mainline and reduce travel time (Cambridge Systematic, 2001). In this study the speed in the mainline was increased by 15%, which decreased the number of crashes occurring on the motorway by 26%. Other studies show that ramp metering helps to reduce speed variation and the length of queues on the mainline which leads to greater safety (Abdel-Aty, M. 2007) and helps to reduce real-time crash risk along the freeway (Abdel-Aty and Gayah V.V. 2009)

Ramp metering strategies can be classified based on traffic responsiveness;

- Fixed time/ pre-timed/time of day ramp metering also called static optimal control. These strategies are determined off-line and based on historical demand (traffic data). Different ramp metering rate will be set for different times of the day according to the demand.
The advantages of these strategies are that they allow the number of served vehicles, to be minimized the total distance travelled to be minimized, or ramp queues balanced. The drawback of applying these strategies is that they do not consider demand variation over the day or day to day, which potentially could lead to overload of the main stream during high demand or underutilization during period of low demand on the motorway. The fixed time ramp metering strategy was extended to dynamic control strategy by Papageorgiou (1980).

- Reactive ramp metering also called dynamic optimal control. These strategies are determined on-line and based on real time traffic data on the motorway to determine the control policy. Traffic data such as flow, speed and occupancy will be detected and the metering rates vary over time.

Reactive ramp metering has similar advantages to fixed time ramp metering. Reactive ramp metering, however, stands out for its ability to even prevent congestion

Reactive ramp metering strategies can be classified as the follows:

- Local control (isolated), where control is performed independently. Traffic conditions are measured locally and can thereby impact local congestion in the vicinity of the metered ramp.

- Coordinated control where a group of on-ramps controllers on the motorway will be coordinated taking traffic conditions in the whole facility into consideration. Traffic conditions are measured on longish sections of the motorway. The aim of coordination is to achieve optimal traffic condition for the whole system. This group includes cooperative ramp metering, competitive ramp metering and integral ramp metering.

Over the last year, many different ramp metering algorithms have been proposed and some of them are already in operation in the field. Different ramp metering control methodologies are reviewed and evaluated, see review (Zhang, M., et. al., 2001).

Several traffic signal operation policies for ramp metering have been developed recently, see the overview of four practiced metering policies by (Papageorgiou, M. and Papamichail, I., 2008). These include: One-Car-Per-Green., where the green time is fixed to allow one car to pass at each cycle. N cars-Per-Green, Full Traffic Cycle and Discrete Release Rates.

Studies by (Kotsialos, A., Papageorgiou, M., 2001; Kotsialos, A. et al., 2002) demonstrate that efficient ramp metering strategies employing optimal control algorithms may lead to as much as a 50% reduction in time spent in large-scale freeway networks.

2.3.1 Ramp Metering Strategies

The most well known local ramp metering strategies are the demand-capacity strategy (Masher et. al., 1975) and ALINEA (Papageorgio et al. 1991). Different ramp metering control methodologies have been reviewed and evaluated, see the review by (Zhang Michael 2001). In the demand-capacity strategy flow and occupancy data from of the mainstream upstream of the on-ramp are collected, while in ALINEA occupancy data from of the mainstream at downstream of the on ramp are collected.
The ALINEA Algorithm

ALINEA (Asservissement Linéaire d’Entrée Autoroutière) is a simple local reactive ramp metering strategy based on a feedback principle proposed by Papageorgiou et. al. (1991). Real-time traffic measurement in the vicinity will be collected to calculate suitable metering rates with the aim of maintaining an optimal occupancy on the mainline such that the combined flow from the main stream and on-ramp will not exceed system capacity.

Ramp metering rate is determined based on local conditions such as real time flow and occupancy data. ALINEA (figure 2.9), requires one detector station in the desired location on the mainline immediately downstream of the entrance ramp to measure the occupancy \( O_{out} \), the constant \( K_r \), and the update cycle of each metering rate. The advantage of ALINEA is its ability to react even to slight differences between \( O_{out}(k) \) and \( O_c \) and thus may prevent congestion by stabilizing the traffic flow at a high throughput level (Pappageriorgiou, M. et. al. 2003). Regardless of the upstream traffic flow, the feedback law in ALINEA attempts to attain desired occupancy. The closed loop feedback in ALINEA uses the following equation (Papageorgiou 1991) to determine the current ramp metering rate for each on-ramp:

\[
q_{in} \quad r(k) \quad O_{out} \quad q_{out} \quad q_{cap} \\
\]

\[
r(k) = r(k-1) + K_R \left[ \hat{O} - O_{out}(k-1) \right]
\]

where:

\[
k = 1,2, \quad \text{is the discrete time index}
\]

\[
r(k) \quad \text{is the ramp flow (veh/h) allowed to enter in time period } k
\]

\[
r(k-1) \quad \text{is the metering rate in time step } k-1;
\]

\[
O_{out}(k-1) \quad \text{is the last measured downstream motorway occupancy (in \%)} \text{ average over all lanes}
\]

\[
\hat{O} \quad \text{is the desired occupancy.}
\]

\[
K_R \quad \text{is the regulator parameter}
\]

The regulator parameter \( K_R \) is used for adjusting the constant disturbances of the feedback control. It was found that in real-life experiments, a value of \( KR = 70 \) vehicle/hour gave good results. Larger \( K_R \) values tend to reduce the regulation time and lead to stronger reaction.

\( \hat{O} \) is a set (desired) value for the occupancy downstream station (\( \hat{O} \) may be set equal to usually equal to or less than critical occupancy \( O_{cr} \), in which downstream motorway flow
becomes close to $q_{cap}$). The range of values for this parameter varies between 18% and 31% (Chu and Yang, 2003).

The downstream detector should be located between 40m and 500m downstream of the on-ramp to effectively react to an excessive traffic flow created from the on-ramp, Chu and Yang, (2003). Closer location of the downstream detector to the ramp merging point will impact the cycle rate of the ramp metering and will demand shorter cycle time. This will avoid congestion build-up in the interior of the stretch from the ramp nose to the detector. It is recommended that the metering rate cycle range be set to between 40 seconds and 5 minutes.

The application of ramp metering can lead to the formation of an on-ramp queue. If the queue length exceeds a certain limit such that interference with the surface street traffic appears, the ramp metering is temporarily disengaged (queue override) to allow a decrease of the ramp queue (Smaragdis, E. and Papagiourgiou, M., 2004). Later studies considers queues at ramp (Papageorgiou, M. and Papamichail, I., 2008). As a consequence of ramp metering, the queue spill-back of vehicles tends to enter the main line quickly but is hindered by ramp metering. Papageorgiou and Papamichail, I. (2008) propose a counter-measure against ramp queue spill-back, which is queue override. They suggest that a loop detector to be placed at the upstream end of the entrance ramp to detect excessive queue length. The ALINEA algorithm does not consider the queue spill-back, as this is not implemented in the algorithm. It is common for any kind of control will be unsuccessful in congested condition (Zhang et al. 2001).

### 2.4 EVALUATION STUDIES

Motorway control strategies in general and VSL in particular have been evaluated through both field tests and simulation experiments.

#### 2.4.1 VSL evaluation studies

**A. Field studies**

VSL strategies aim to increase safety by warning drivers upstream of queue downstream by displaying lower speed limits. Two main strategies for generating VSL have been discussed in the literature. The first aims to homogenize the flow in order to achieve stable and safer flow and reduce congestions (Smulders, S., 1990), and the second to prevent traffic breakdown and resolve shockwaves (Hegyi, A., 2004).

Most link control applications emphasize homogenization or stabilization effects, e.g. (Pirkko, R., 2001; Smulders, S., 1990, 1996; Zackor, H., 1979). The main characteristics of the homogenization measures are as follows (Smulders, S., 1992):

- Control by reduced speed limits
- Traffic responsive
- Automatic application in case of high demand
- Preventative

The aim of flow homogenization strategies is not to reduce the mean speed (Cremer, M., 1978), but to try to reduce vehicle distribution and speed differences between or within lanes, thereby minimizing the risk of accidents and congestion upstream of bottleneck locations (Smulders, S., 1990). Van den Hoogen and Shmulders (1994) studied the impacts of a
variable speed limits system on a 20 km segment of 3-lanes of the A2 motorway in the Netherlands between Utrecht and Amsterdam. This system was implemented in 1992 to manage the congested morning and evening peak periods. The objective of the control strategy was to induce a homogenized traffic flow, better speed distribution between lanes and better utilization of lanes. Experiments (Van den Hoogen, E., Smulders, S., 1994) indicate that VSL control reduced speeds in all lanes, speed differential between lanes, the number and severity of shockwaves, and the percentage of headways smaller than 1 second. Occupancies were increased in all lanes and mostly in the outer lane. The study indicates that VSL is not a suitable instrument to eliminate congestion at bottlenecks since the capacity of the roadway is not increased, but it can lessen the effects of the bottlenecks on traffic upstream (Smulders, S., 1990) also reported that homogenization-based VSL can increase the time to breakdown but cannot suppress or resolve shockwaves i.e. speed control is not appropriate for resolving congestion at bottlenecks. Smulders, S., (1992) declares that variable speed limits aim to prevent the occurrence of congestion rather than react to it (incident detection). No capacity increase was mentioned in this particular study.

In several VSL applications lower speed differences between consecutive vehicles, speed variation, and frequency of short headways were observed. Results from an investigation based on traffic data before and after application of the VSL on a two lane German motorway indicate a speed homogenisation effect in the form of less speed differences between consecutive vehicles. Speed dispersion and the frequency of dangerously short time lags between vehicles were all reduced, which he interpreted as an increase in safety (Zackor, H., 1979).

Another approach was used by (Kühne, R.D., 1991) with a control strategy based on mainline control by speed limitation, temporary prohibition of passing trucks, lane keeping, or general warning. The control logic presented for this approach was a combination of several threshold values. Actual traffic density was utilized as a base for deciding whether a specific speed limit should be switched. Because the calculated and measured traffic densities for heavy traffic exhibit fluctuated widely, an additional parameter for threshold comparison of the mean speed was used as the criterion for a safer decision. As a third decision variable, the standard deviation of the speed distribution was used. In this approach, homogenization effects were achieved.

Pirkko, R. (2001) evaluated the effectiveness of Variable Speed Limits implemented on a 14-km section of the E18 in southern Finland. The objective of implementing the system was to improve traffic safety in inclement weather conditions such as slippery road and low visibility. The evaluation study showed that the VSL led to a statistically significant decrease in average speed as well as a decrease in speed variability.

A business case was performed to evaluate the M25 Controlled Motorway in the UK (UK Highway Agency, 2004). The implemented system used an automatic signal setting in response to traffic conditions displaying mandatory speed limits with speed enforcement through the use of automatic camera technology.

The study included a “before” and “after” comparison of key variables such as journey time, overall amount of breakdown, safety, and capacity. The results showed that MCS led to a 10% reduction in the number of injury accidents. Although the impact on journey time was small, journey time reliability improved in certain key periods. A more balanced lane distribution was also obtained, as well as a reduction in speed differential between lanes and a
more uniform distribution of headways in most periods. The latter improvements led to a reduction in the number of lane changes for overtaking. Vehicle emissions were reduced by MCS as stop-start driving was reduced by 6% and compliance with speed limits improved.

Flow limitation based strategies for generation of VSL endeavour to reduce or eliminate shockwaves on freeways. Hegyi, (2004) describes three states of traffic flow: stable, meta-stable, and unstable. He explains the levels of disturbance related to these states. Stable means that any disturbance (no matter how large) will vanish without intervention. Meta-stable means that small disturbances will vanish, but large disturbances will create shockwaves.

During unstable traffic flows, the shockwave is triggered by any disturbance no matter how small. To dissolve the shockwave, he proposes using speed limits to limit traffic flow. Hegyi states; “traffic flow must be in a meta-stable state, because in the stable state there is not much to control”. He further states that the speed limit can limit traffic flow without creating large disturbances. Flow limitation based strategies attempt to reduce the lengths of traffic jams by reducing inflow. Traffic upstream is slowed down and this, in turn, reduces the inflow into the traffic jam and thereby delays the onset of congestion (Popov, A., 2008 and Hegyi, A. 2004).

Hegyi, (2004) proposed the Model Predicted Control (MPC) method to reduce shockwaves. This was applied to a network consisting of a link of 12 km, where 6 segments of 1 km were controlled by speed limits. The idea was to impose speed limits and consequently reduce the inflow to the jammed area. When the inflow to the jammed area was smaller than its outflow, the jam would eventually dissolve. The speed limits created low density waves that propagated downstream. The method uses a centralized controller with a macroscopic traffic model to predict the future traffic states over a prediction horizon and determine the optimal speed limits. Subsequently, a decentralized control method was also developed, that uses local information (Popov, A, 2008, and Lin, P. W., Kang et al. 2004). Simulation results from a case study on the A12 freeway in the Netherlands show that the method successfully resolves shockwaves and reduces the total time spent by approximately 21% compared to the uncontrolled case.

Most of the earlier studies focused on the impacts of VSL on individual traffic variables (traffic flow distribution, mean speed, mean headway, etc). The author’s conclusion regarding results from these studies is that there is very limited empirical evidence regarding the impact of VSL on traffic behaviour. The problem with field studies is that it is very difficult to isolate the impact of VSL from other factors that may contribute to whatever changes are observed.

Later studies Zackor, H. (1991) were focused on the impact of the VSL on the fundamental diagram. Figure 2.10 illustrates the relationship between traffic flow and density for two cases with and without VSL. It can be seen that at lower or mean traffic flow the mean speed is low due to the reduction effect, whereas for higher traffic flows the mean speed is higher due to stabilizing effect. Due to improved flow stability the capacity also increased by 5% and the speed increased by 10%. In this study, the impact of VSL on increases in critical occupancy was not commented upon.
However, most recently, Papageorgiou, et al. (2008), has examined the impact of mandatory VSL using the corresponding flow-occupancy diagram. They applied the method using flow-occupancy data before and after the implementation of mandatory VSL on a European motorway. The VSL used a flow/speed threshold based control strategy. The main goal of the investigation was to examine whether the speed limits modify the shape of the flow-occupancy diagram. The occupancy axis was divided into intervals of equal length and a 2\textsuperscript{nd} order polynomial curve-fitting was performed for each interval.

The study found that VSL reduces the slope of the (flow-occupancy) graph at under critical occupancies and shifts the critical occupancy to higher values in the flow-occupancy diagram. This enables higher flows at the same occupancy values in overcritical conditions. The results from the study were not conclusive regarding the impact of VSL on the capacity of the facility. The results of the study also indicated that a VSL control strategy using the slope of the occupancy-flow curve, estimated in real time, as an indicator for VSL activation, may result in more effective and robust VSL strategies.

**B. Simulation studies**

Different simulation studies were also performed to study the impact of the VSL. Several researchers have recently developed and applied microsimulation models to study the impact of ITS. The homogenization method was tested using SISTM (Simulation of Strategies for Traffic on Motorways), a microscopic motorway simulation program, which was enhanced to model variable speed limit systems operated on the in M25 in the UK, through the utilization of the collected speed, volume and density data, homogenization control logic was applied for switching between the speed limit values. Results from the study showed that with no speed limits, there was a wide variation in individual target speeds (Hardman, E. J., 1996).

Yang, Q. and Koutsopoulos, H. N. (1996) developed a Microscopic Traffic SIMulator (MITSIM), for modelling traffic flows in networks with advanced traffic control, route guidance and surveillance systems. Results from the case study in the A10 beltway in Amsterdam with non-recurrent congestion show that a saving in travel time of 2-4% was
achieved when real-time traffic information was provided to 30% of the drivers. Gardes, Y. et. al. (2002) applied the Paramics traffic microsimulation model, and assesses its ability to serve as a tool for evaluating potential freeway improvement strategies that include ramp metering, auxiliary lanes, and HOV lanes. Barceló, J. (2001) presented AIMSUN2 microsimulation model specifically designed for assessing ITS systems deployment including ramp control and adaptive control systems which prioritise public transport. Gomes, G. et. al. (2004) applied the VISSIM microsimulation model to a congested freeway presenting several complicating features: an HOV lane with an intermittent barrier, and several metered on-ramps with and without HOV bypass lanes. Al-Deek, H. (2005) applied PARAMICS to evaluate the effectiveness of alternative toll pricing scenarios as traffic diversion strategies on toll and non toll facilities in the studied network. Zhang, G. et al. (2008) conduct a study using VISSIM to evaluate a proposed feedback-based tolling algorithm to dynamically optimize High Occupancy Toll (HOT) lane operations and performance. The test results show that the proposed tolling algorithm performed reasonably well in optimizing overall traffic operation with the HOT lane system under various traffic conditions. Many researchers stress the importance of accurate calibration and validation of the simulation models prior to their application in the assessment of various traffic operation and management strategies (Yang, Q. et al. 1996 and Gardes, Y. et al. 2002, and Park, B., and H. Qi, (2008)). Treiber, M. and Helbing, D. (2001), used a microsimulation model to study the impact of VSL, on-ramp control and vehicle-based driver assistance system on freeway traffic. Results from a section of the German autobahn A8-east showed that both speed limit and on-ramp control could considerably reduce the severity of the originally observed and simulated congestion.

Various VSL strategies have been used as a tool for safety improvements on freeway. Using the PARAMICS microsimulation model to evaluate the impact of the VSL on safety, Abdel-Aty, M et al. (2005) studied a section of Interstate 4 in Orlando, Florida. The results indicate that the implementation of the VSL produced safety improvement by simultaneously implementing lower speed limits upstream and higher speed limits downstream of the location where crash likelihood is observed in real time. The important results from the study point out that no substantial safety benefit from implementing VSL was achieved in congested situations.

**C. VSL and driver behaviour**

Motorway Control Systems are in general based on closed feedback loops. This type of management control is complex and dynamic, and depends on the interaction of all components in the system. The communication network for MCS is vital to the operation of the system and must be reliable.

One important component in the control loop for Variable Speed Control is the involvement of human driver behaviour and the randomness in following the displayed information. These behaviours are difficult to detect and add uncertainty to the problem of controlling freeway traffic. All this makes the use of Variable Speed Limits to obtain optimal freeway control a difficult task. Chien (1997) declares the involvement of human drivers for microscopic vehicle control and the randomness in following advisory message signs as a reason why feedback control is difficult to apply effectively.

In general, VSL systems can be implemented as advisory, e.g. like the system in Stockholm and the VSL system implemented on a two-lane German motorway (Robinson, M., 2000), or mandatory such as the M25 Controlled Motorway round London (UK Highway Agency, 2004). The latter method results in a more stable traffic flow since drivers respond and accept
the system better (Messmer, A. and Papageorgiou, M., 1994), (Kotsialos, A. and M. Papageorgiou, 2004), (Zackor, H., 1979) and (Smulders, S, 1990). In the case of advisory VSL, studies indicate that enforcement is necessary to achieve and maintain a sufficient level of acceptance.

The application of advisory speeds was discussed in Smulders, 1990. A hystereses control law for turning the control action on and off was proposed. This control law is dependent on the freeway density value. The hystereses clearly enable a reduction in the frequency of switching. Frequent switching would confuse drivers and might be dangerous if the drivers do not comply.

The success of VSL depends to a large extent on how drivers respond to the displayed speed limits, and interact with other drivers. Studies on the M25 motorway round London, in the UK (UK Highway Agency, 2004) show that safety benefits of VSL systems arise as a result of adjustments in driving behaviour. Drivers kept more uniform headways, which resulted in reduced braking. Accidents with injuries were reduced by 10%. Furthermore, traffic noise was reduced by 0.7 decibels, and fuel consumption, and thereby emissions, were reduced by 2-8% overall.

Studies have shown that compliance with the displayed speed leads to reduced speed variance, more uniform headways, better utilization of all lanes, and a stable or harmonized traffic flow, resulting in less risk of shockwaves and congestion, (UK Highway Agency, 2004). It may also improve driving comfort, improve road safety, and reduce fuel consumption and emissions as a result of fewer acceleration/deceleration manoeuvres (Den Tonkelaar, W.A.M., 1994)

2.4.2 Ramp metering studies

Two methods are used in the evaluation of ramp control systems, field operational tests and computer simulation. In the review of road traffic control strategies (Papageorgiou et al 2003) mentioned a field based evaluation of ramp metering using ALINEA and other ramp metering strategies including demand capacity and percent occupancy. In this study Ramp metering was applied in the field at a single on-ramp on the Boulevard Peripherique in Paris. These strategies were evaluated and ALINEA led to a maximum improvement considering of 16% less total travel time spent on the main-line, 23 %, increase in mean speed and 51% reduction in congestion duration.

Different simulation studies have been conducted to test various ramp control strategies. Efficient ramp metering strategies (employing optimal control algorithms) reduce the total travel time spent in large scale freeway network by 50% ((Papageorgiou, M. and Kotsialos, A, 2002) and constitute the most direct and efficient way to control and upgrade freeway traffic (Papageorgiou 2003).

Zhang, M. et al., 2001 adopted Paramics as the simulation platform for evaluation of selected ramp metering algorithms. This study shows that ramp metering reduces vehicles’ total travel time by up to 7% compared with no metering. The effectiveness of a ramp control algorithm depends on the level of traffic demand.

A later study considers queues at ramps (Papageorgiou, M. and Papamichail, I., 2008). As a consequence of ramp metering, the queue spills-back of vehicles tends to enter the main line
quickly but is hindered by ramp metering. Papageorgiou M. and Papamichail, I. (2008) propose a counter measure against ramp queue spill back which is queue override. They suggest that a loop detector be placed at the entrance to the on-ramp.

PARAMICS was also used in (Abdel-Aty and Vikash, V. G. 2009) to compare two different ramp metering algorithms containing ALINEA and Zone algorithms, for real time crash risk reduction. The study shows that ramp metering can be applied to a congested freeway to successfully reduce both rear-end and lane change crash risk along the freeway in real-time.

Hourdakis, J. and Michalopoulos, P. G. 2002, applied the AIMSUN microscopic model to evaluate ramp control effectiveness in the Twin Cities metropolitan area of Minnesota. For this area 430 ramp meters were shut down to evaluate their effectiveness. The Zone control algorithm was implemented. The evaluation of with and without ramp metering shows that without ramp metering there were an average traffic volume reduction on the freeways of 9 % and speeds on the freeways were decreased, which led to longer travel time. The number of crashes increased by 26% and emissions were reduced while fuel consumption, which was the only criterion increased by ramp metering rose.

Different types of control strategies have different objectives. These types of control strategies are usually designed and implemented separately. Differentiation in applied strategies may solve congestion in a local area but vehicles might encounter congestion in another area. However, different control strategies can be applied as coordinated or integrated control measures. According to (Papageorgiou, M., Kotsialos, A., 2002), coordinated control strategies consider multiple control measures of the same type while integrated control strategies consider different types of control measures. Arguments for the need to coordinate variable speed limits in order to prevent the occurrence of new shockwaves and/or a negative impact on the traffic flows in other locations have also been found in Hegyi, (2003).

Hegyi, A., (2004) modelled integrated ramp metering and variable speed limits. His study was aimed at improving the traffic flow by preventing traffic break-down. Integrated ramp metering and variable speed limits resulted in a 14.3% improvement in Total Time Spent (TTS) compared with the no-control case.

As early as 2003, Chu, L. and Yang, X. stated that the successful application of ALINEA depends upon the correct determination of the following parameters: the update cycle of metering control, a constant regulator used to adjust the constant disturbances of the feedback control, the location of the desired occupancy of the downstream detector station. Adjustment of these parameters resulted in increase in mainline throughput, utilize freeway capacity, and reduce both duration and extension of recurrent congestion and increase traffic safety due to reduce congestion and safer merging.

This improvement was achieved at expense the cost of traffic conditions upstream of the on-ramp. Hindered vehicles tending to enter the mainline to keep a smooth traffic flow in the later could lead to a spillback of vehicles on the on-ramp which may result in congestion in secondary arterial roads and even blockage of upstream intersections. In a later study (Papageorgiou, M. and Papamichail, I., 2008) considered the queue at upstream of on ramps. They propose a counter-measure against ramp queue spill-back, override was proposed where it is suggested that loop detector be placed at the entrance to the on-ramp.
2.5 SUMMARY AND CONCLUSIONS

Over the last thirty years, development of the Intelligent Transport Systems technology has led to new ways of managing and operating existing transportation infrastructure. The aim has been to increase efficiency, reliability, and safety, as well as reduce the loading on the environment, without necessitating major physical changes in the road infrastructure. Based on the literature review, the following summary of impacts of Variable Speed Limits and Ramp Metering is presented.

For Variable Speed Limit systems a distinction is made between approaches aimed at homogenizing the flow and approaches aimed at resolving shock waves or jams. VSL systems are implemented as advisory or mandatory (enforced).

Flow homogenization strategies endeavour to reduce vehicle distribution and speed differences between lanes, thereby minimizing the risk of accidents and congestion upstream of bottleneck locations. Under this strategy, VSL are generally applied when traffic volumes are close to capacity. It is also reported that homogenization-based VSL can increase the time to breakdown but cannot suppress or resolve shockwaves.

Flow limitation based strategies for generation of VSL aim to reduce or eliminate shockwaves on motorways. These strategies endeavour to reduce the lengths of traffic jams by reducing inflow. Traffic upstream is slowed down and this in turn reduces the inflow into the traffic jam and thereby delays the onset of congestion. Shockwaves eliminating approaches allow speed limits that are lower than the critical speed in order to limit the inflow to bottleneck areas.

In general, the impact and effectiveness of mainline control strategies have not been extensively studied and constitute perhaps one of the least studied areas within motorway traffic control (Messmer et al., 1994). Kotsialos et al. (2004) report that few systematic studies have been conducted to quantify the impact of link control measures, e.g. studies such as (Zackor, H. 1979 and Smulders, S.1990). Furthermore, Messmer et al. (1994) suggest that the impact of link control has to be well understood in order to optimize the design of such systems. Similarly, the literature on empirical evaluation of VSL systems is very limited, both from the point of view of methods for the evaluation of such systems, and empirical evidence and systematic analysis regarding their effectiveness.

Most of the earlier studies focused on the impacts of VSL on individual traffic variables (traffic flow distribution, mean speed, mean headway, etc). The problem with such approaches is that it is very difficult to isolate the impact of other factors that may contribute to whatever changes are observed. However, most recently, Papageorgiou, et al. (2008), examined the impact of mandatory VSL using the corresponding flow-occupancy diagram. They applied the method using flow-occupancy data before and after the implementation of mandatory VSL on an European motorway.

In recent years, simulation has emerged as an alternative tool to evaluate the performance of dynamic traffic controls and to select an appropriate design. Different scenarios can be used to test and evaluate the proposed system design and control. In the literature different studies can be found where simulation models are used to evaluate different types of dynamic control.

Traffic simulations were used to study the impacts of driver compliance on the effectiveness of advisory VSL. Simulation models have the ability to capture the dynamic behaviour of the
individual divers as they react to the perceived traffic situation and controls. Microscopic traffic simulation models allow detailed representation of the traffic control system under study and capture the behaviour of drivers in response to developing traffic conditions, and are particularly well suited to evaluate ITS. However, the models must be calibrated and validated for the studied conditions before any conclusions can be drawn from their application.

The existing ramp metering strategies are categorized according to several properties. Ramp metering can be used in two different modes: spreading mode and restricting mode. The spreading mode endeavours to reduce the probability of a breakdown caused by a platoon of vehicles arriving from the on-ramp. The restricting mode endeavour to redirect drivers to other routes or prevent demands levels that exceed motorway capacity.

Several ramp metering strategies have been developed, including static or dynamic, fixed-time or traffic-responsive, and local or coordinated. Different simulation studies have been conducted to test various ramp control strategies.

Different types of evaluation were found in the literature including empirical evaluation or field operational tests and simulation studies of VSL and ramp control systems. Field operational tests tend to be expensive, time consuming, and sometimes impracticable. The results gained in the field always depend on tests performed on uncontrolled elements such as weather, demand variations, incidents etc. which lead to an inaccurate analysis of the impact of the applied control. The results of the analysis will then not be plausible due to the confounding effects.

In simulation studies the testing conditions can be easily controlled by means of a before and after study. The simulation model can also be applied to design, evaluate and test different scenarios.

An important aspect when evaluating VSL is to be able to attack the problem from different angles and compare behaviour before and after applying VSL. Studying the actual behaviour of the drivers, by applying a research strategy based on a “bottom up” micro-approach. The approach can be based on empirical studies of such responses and their impacts on the overall traffic process. Other aspects include studying the impact of the VSL on aggregated data, on the fundamental diagram i.e. (speed-density) and applying simulation to model and control all variables that may impact the test and test different scenarios that may improve the system. All this is intended to constitute a framework for the assessment of the impact of VLS and discuss its application in a case study involving an advisory VSL system in Swedish capital of Stockholm.
CHAPTER 3 THE MOTORWAY CONTROL SYSTEM (MCS) IN STOCKHOLM

3.1 INTRODUCTION

Stockholm is built on several islands in the water connecting the Baltic with the inland lake system, which provides charm but also causes traffic problems, see figure 3.1. It is the country’s largest urban area with a population of some 1.9 million. As in most metropolitan cities, the traffic situation in Stockholm is a problem; the capacity of the streets and roads during rush hour is simply inadequate. A bigger population and positive economic growth will lead to even greater congestion since the expansion of the motorway network is limited for political, environmental and economic reasons.

The E4 motorway, which passes to the west of the city, is highly congested. This stretch has the highest traffic volume in all of Sweden. It connects the southern and northern parts of Stockholm and is an important link to Arlanda, Sweden’s most important airport. The capacity of the E4 motorway is constrained by its infrastructure design. To circumvent the geometric limitation of the road capacity, a Motorway Control System (MCS) was implemented on the E4 to accommodate a stretch of road through Stockholm. The northern part of the motorway, Uppsalavägen (8 km), has been equipped with a Motorway Control System (MCS) since 1996. An extension of the MCS system on the southern part, Södertäljevägen, (12 km), was implemented in 2004.

Three main arterials have to cope with most of the north-south traffic; Västerbron, (AADT 124,000), Central Bridge (AADT 36,000), and E4 Essingeleden, (AADT 140,000), (Baradaran, S. et al., 2005). These bridges form the backbone of Stockholm’s road transport system and must be used as efficiently as possible.

Figure 3.1. The main highways through Stockholm city.
The traffic situation in Stockholm can be summarized as follows:

- Some 4 million trips are made every day in Greater Stockholm.
- About 75% of all commuter trips across city limits during rush hour are made by public transport.
- 45% of all job opportunities in Greater Stockholm are found within the inner city limits.
- Major parts of the arterial road network in Stockholm experience recurrent congestion. The rush hour is steadily expanding - from 6.30 until 9.30 in the morning and from 4 o’clock until 6.30 in the evening.

Road traffic networks that operate close to capacity are very prone to frequent incidents (accidents, stalled vehicles, road works, etc.) that reduce their performance. The frequency, duration, and impacts of such incidents on the Stockholm arterial network are thus of great importance for how well the network and its traffic control system function.

The reasons for implementing MCS were to:
- increase traffic safety by earlier warnings of queues
- increase capacity during peak traffic by reducing speed variance
- improve the environment by reducing traffic impact through smooth traffic flows
- facilitate road work and incident management through the use of VSL to indicate lane closures

### 3.2 STOCKHOLM MOTORWAY CONTROL SYSTEM (MCS)

Policy makers have to deal with the continuous growth of traffic, which leads to a demand for increased network capacity. The Swedish Parliament adopted a transport policy based upon the Government Bill (1997/98:56) "Transport Policy for Sustainable Development", that contains overall and specific traffic policy objectives (Regeringskansliet, 2003). This was reviewed 2009. According to this policy, it is important to design the future transport system so that it meets high demands as regards transport quality, accessibility in order to meet the basic transport needs of citizens and businesses, safety, and positive regional development.

Stockholm suffers from road traffic congestion due the difficulties in providing a much-needed capacity expansion of its road networks, which includes many major bridges between the islands on which the city is built. The E4 motorway west of the city serves most of traffic passing through Stockholm from south to north and vice versa. This road is so heavily overloaded today, that even minor incidents can cause serious traffic problems. The capacity of the streets and roads during rush hour is simply inadequate.

Stockholm’s road traffic authorities have therefore made considerable efforts to implement traffic management including the use of Intelligent Traffic Systems (ITS). The Motorway Control System (MCS) installed on the E4 motorway through Stockholm is one example of such measure, see figure 3.2.
Implementation of ITS applications began in 1996, with the aim of providing travellers with information and guidance and enabling the operators to monitor traffic in general and keep a close watch on traffic in the city and on main access roads. Within the programme, cameras, sensors and information systems that can be used to manage traffic have been installed along Stockholm’s E4 motorway and in tunnels.

MCS includes subsystems and components designed to inform and warn drivers and control their choice of speed and lane selection with the objective of harmonizing traffic flow and reducing delay. Variable speed control and incident detection and management are two means to accomplish this. These components can either work alone or be combined. The MCS includes the following:

- Speed control, by which the advised/recommended speed is displayed continuously (e.g. each 500 m) by using variable massage signs mounted on gantries.

- Lane control, where the drivers are requested to change lane in case of a temporary lane closure downstream due to an incident or road works.

The Motorway Control Systems (MCS) that are installed on certain motorway sections in Stockholm (E4) and Gothenburg (Lundby tunnel) provide automatic warnings of queues or slow-moving traffic ahead. Traffic is warned and slowed down by means of flashers and speed signs on the gantries upstream of a queue tailback. MCS is based on a similar system called MTM that is currently in operation on many parts of the Dutch motorway network.

MCS uses an Automatic Incident Detection (AID) algorithm that detects slow traffic as a basis for the activation of speed signs showing gradually decreasing velocity legends on Variable Speed Limits (VSL) mounted on the MCS gantries.
Although the system implemented on the E4 motorway in Stockholm has been in operation since 1996 and is currently being expanded. Knowledge regarding the impacts of the system on traffic safety and performance is still largely lacking. It is therefore important to undertake research that will lead to improved knowledge to support investment and implementation of ITS as an alternative or complement to capacity expansion through road investments.

Other existing problems with MCS are related to its operation in specific cases; no consensus exists on the desired legends with respect to different traffic situations. The Automatic Incident Detection (AID) algorithm imbedded in the MCS system could also be improved or adjusted more accurately.

MCS is a complex system because it covers a large area consisting of different kinds of traffic installations and traffic conditions. At the same time, the system depends on road-users’ acceptance and behaviour with different types of traffic control and traffic information. The impact of these systems is difficult to estimate because of their dynamic characteristics.

A better understanding of motorway operations under congested conditions is also needed in order to:

a- Identify critical density and critical speed
b- Foresee when to apply the control measure to reduce speed limits to critical or lower just before the critical speed is reached
c- Achieve better utilization of the motorway infrastructure

3.3 SYSTEM DESCRIPTION

The total implemented stretch of Motorway Control System (MCS) covers a road length of 20 km, with 3-4 lanes per direction consisting of basic motorway segments and weaving segments and including 64 on/off ramp connections. Crash barriers separate the two carriageways. The posted speed limits vary from 70 to 90 km/h for different stretches of the motorway.

This motorway experiences heavy congestion during morning and evening peak hours. The longer the carriageway remains blocked by vehicles involved in accidents and traffic delay, the longer the inconvenience lasts. Assistance and emergency services need to be summoned as quickly as possible. Reducing the time gap between occurrence of accident and commencement of rescue operations is vital to reducing accident strain and damage.

The information collected by the detectors (local control) enables the system to automatically regulate recommended speeds, which can also be controlled manually. This information is also sent to the Traffic Management Centre where operators are on duty 24 hours a day. They operate the system; verify incidents and accidents via the cameras, and direct emergency services (Police and VägAssistans1) to the proper location. The detected information sent by the outstations enables the system to automatically regulate traffic speeds. Operators can also take manual control and monitor traffic via the Variable Message Signs.

1 VägAssistans, established in 1996, consists of a number of vehicles and motorcycles that can be deployed to assist drivers in difficulties.
Traffic information is sent to radio stations and Radio Data Systems and Traffic Message Channels (RDS and RDS/TMC), see figure 3.3. Information regarding (disrupted) traffic flow, accidents, road works, parking spaces, and special events is communicated both by local radio stations and variable message signs.

The ability to collect vehicle counts, measure the speed values as long as a moving vehicle is in the radar beam, ensures that slow-moving traffic will be warned in advance by showing successively decreasing speed signs on the gantries upstream. This allows traffic management centre “Trafik Stockholm” to both evaluate the performance of the transportation network and monitor the system for irregular conditions and levels of congestion. The centre is also responsible for the safety of tunnel operations in Södra Länken. The latter includes checking exhaust fumes and air quotients and guaranteeing clear access for emergency services. Another surveillance system informs the operators of any malfunctioning of traffic lights.

The SRA co-operates with Stockholm’s municipal authorities, the police, the fire department, and SOS Alarm in order to improve (the speed of) assistance in case of an incident.

Figure 3.3. Stockholm’s Traffic Management Centre “Trafik Stockholm”.

The MCS is equipped with an Automatic Incident Detection (AID), which detects serious disturbances in the traffic streams as soon as possible and automatically generates a suitable set of advisory speed limits for the approaching traffic. The recommended Variable Speed Limits (VSL) speeds are displayed on signs mounted on gantries every 500 m along the motorway. The gantries also have microwave detectors to measure traffic volumes and speeds. Detected speeds provide the input data required by the automatic incident detection (AID) algorithm. The VSL is based on closed feedback loop logic.
3.3.1 System characteristics

Motorway traffic management using Intelligent Traffic Systems (ITS) is generally based on the concept of interaction between system and road users, based on the collection, processing, and distribution of information about traffic conditions as Figure 3.4 illustrates.

![Figure 3.4. Closed loop chain event of the MCS.](image)

In MCS, this involves the following processes:

1- Traffic surveillance for recording the actual traffic situations
   Microwave detectors in each lane spaced by 300-500 m apart collect information regarding, flow, speed, occupancy and headways which is aggregated as one-minute averages. A floating average of speed is also calculated as a basis for automatic incident detection alarms (AID). CCVT surveillance verifies AID alarms and traffic conditions.

2- Lane signalling using VSL for communication with drivers
   AID alarms trigger pre-determined lane-signalling plans aimed at reducing the speed of traffic approaching the location of the detected incident. These signals are displayed by variable message lane signals mounted on gantries above each lane every 500 m. These signals can show recommended speed or lane closure.

3- Driver response to the lane signalling and surrounding traffic situation
   Drivers approaching a gantry with activated lane signals can react in different ways:
   - Ignore the signal message
   - Change their behaviour, speed, and/or selected lane in response to the signal

4- Impact of changed driver behaviour
   The purpose of MCS is that the drivers will change their behaviour in ways that will improve traffic safety and/or the state of traffic performance.

The MCS in Stockholm is a hierarchically organized, with three main components, see figure 3.5:

- The central computer system (CS)
- Outstations (OS), each connected to two gantries with one matrix sign per lane
- Detector stations (DS) and detectors
The system can also operate in local mode if the connection to the CS is not functioning.

In addition, there are several CCTV (Closed Circuit Television) cameras that cover road segments. These cover a large area and are used by the operators in the traffic centre, called “Trafik Stockholm”, to monitor traffic and verify and manage incidents, i.e. decide what kind of action to take.

Detector station (DS)
Initially the system was equipped with double inductive loop detectors in every lane. In 2003 these were replaced with microwave detectors because of winter maintenance problems. The microwave detectors are placed on the gantries above each lane and provide information about traffic flow, average speed, and headway per minute.

The detectors used in the MCS system are mounted on the lower edge of the matrix signals, which are in turn located on gantries over each lane. The detectors are directed towards each lane at specific measurement angles between $30^\circ$ and $60^\circ$, see figure 3.6.
The detectors have two completely different operating modes for application purposes: tracking mode and counting mode. Typical applications in tracking mode are speed displays, excess speed warning systems, etc. with small measurement angles and high distance ranges. The most important aspect for these systems is that they can detect changes in a vehicle’s speed in the radar beam for a desired distance. The detector thus delivers speed values as long as a moving vehicle is in the radar beam.

**Outstations (OS)**

The outstations (OS) are coupled to the gantries. One OS is connected to two detector stations. The detector stations measure the velocity of each car in each lane. The OS preprocesses traffic data, in particular the AID requests, and sends the results to the CS. The OS switches the legend on the matrix signs on its gantry when it is instructed to do so by the CS. When the connection to the CS is not functioning for some reason, the OS operates independently. This autonomous mode is called “Local mode”.

**Central system (CS)**

The CS is responsible for communicating with the outstations, processing the outstations’ AID requests, calculating the new messages, and sending back instructions to the outstations for displaying the messages on their signs. The CS maintains the coherence of the pattern of showing legend as a whole. It processes more general traffic and status data and handles operator requests. To this end, the CS is connected to user terminals.

The CS continuously participates in closed loop AID with the outstations that are in normal mode. They may be either in closed loop AID mode (CLA), which is the normal condition, or in local mode (LMA). In CLA, the CS is in the lead to instruct the OS which legends to display; in LMA the OS decides for itself.

### 3.3.2 Messages displayed

MCS communicates with drivers through Variable Speed Limits (VSL) of the fibre optic type. The signs can display recommend speeds (white figures), recommended lane change (yellow arrow) and indicate lane closures (red crosses) and display the ends of restrictions (end of limit). The latter signs are used only when cross or arrow signs terminate, see figure 3.7. The VSLs are enhanced with flashers in cases where signal signs change, e.g. 50 flash, 50, 30 flash and 30.

On the stretch where the posted speed limit is 70 km/h, the leading signal will show 50 km/h and then 30km/h where low speed is detected. When the posted speed limit is 90 km/h, the leading signal will show 70 km/h and then 50km/h where the low speed is detected. The MCS has today an updating frequency of 4 seconds. This is dependent on the arrangement of the parameters of the AID algorithm and how slowly the vehicle needs to be moving to cause the activation of the AID.
3.3.3 Operational Characteristics

The functionality of the MCS system can be summarized as a closed loop event chain where the traffic situation (traffic behaviour) is first detected in the form of traffic flow (number of vehicles per minute per lane), average speed (space mean value per minute per lane), and headway (average headway between vehicles per minute per lane). The speed value is the harmonic mean that is calculated and not the arithmetic mean.

The VSL recommended speed is based on continuous checking (by the outstations) for low speed (usually=queue) at each detection points. If speeds below the present threshold value are detected, this will be communicated to the CS in the form of AID legend requests. The CS applies the legend rules to the current set of requests and the present legend settings on the gantries on the road, resulting in a new desired legend pattern. The CS communicates the required legend changes to the outstations, that then apply the changes to their respective gantries to be displayed on the matrix signs to provide the drivers with information about the current traffic situation. The resulting traffic characteristics in response to the displayed message will be detected and the chain of events will continue according to the actual traffic situation.

3.3.4 Automatic Incident Detection (AID)

The algorithm used in MCS is designed to give alarms when the speed falls below the current threshold values.

AID is implemented on two levels as follows:
- Local mode (local level) with AID from respective outstation and a self-contained algorithm to determine which message to show using VSL.
Normal mode (central level) based detected speed values communicated to CS by the outstations. In normal mode, the outstations await further instructions from the central system, which maintains the coherency in the pattern of legends on the road.

The microwave detector detects the speed of each individual vehicle from which a floating mean speed value is calculated based on the speed of the last few passing vehicles. The speed is obtained by smoothing the measured drive time’s $T_i$ instead directly from the vehicle’s speeds $V_i$.

The smoothed speed is calculated as follows:

- For each vehicle passage a new smoothed average speed value is calculated ($V_{new}$), based on the previous value ($V_{old}$) and the speed of the last detected vehicle.

- A new average speed is estimated for each lane and each detector station. If the previous smoothed average value ($V_{old}$) is missing, the speed of the last detected vehicle will be reported.

The function of the smoothing is to prevent individual measurements leading too quickly to an AID request (Van Toorenburg. et al., 1998). The AID speed feature is a strictly local feature and is calculated once a second for each outstation traffic stream. The smoothing process is undertaken by specifying different values of $\alpha$ for accelerating and decelerating traffic as in the following formula:

$$T_{new} = \alpha_{acc} * T_{measured} + (1-\alpha_{acc}) * T_{old} \text{ for } T_{measured} > T_{old}---(\text{speed increase})$$

$$T_{new} = \alpha_{dec} * T_{measured} + (1-\alpha_{dec}) * T_{old} \text{ for } T_{measured} < T_{old}---(\text{speed decrease})$$

where common values of $\alpha$ are:

$\alpha_{acc}=0.40$

$\alpha_{dec}=0.15$

The measured $T$ is confined by upper and lower limits to prevent extreme measurements giving the smoothed value too much of a push.

$T_{min} < T_{measured} < T_{max}$

where

$T_{max}=S/V_{min}$ $V_{min}$ is set to 18 km/h, and,

$T_{min}=S/V_{max}$ $V_{max}$ is set to 200 km/h.

The reasoning behind the differentiation between speed increase and decrease is that by setting $\alpha_{dec}$ to another value than $\alpha_{acc}$, the speed feature can follow a speed decrease more quickly than a speed increase or vice versa. With the values as given, the system will require more slow-moving cars to react with an AID request when traffic is slowing down than it will
to withdraw the request after a speed increase. These values are chosen according to traffic behaviour and geometry.

Smoothing of the detected speed causes a delay in the speed feature with respect to the actual vehicle speeds when there is a change. It takes a few cars before the speed feature is adapted to a new traffic speed.

Choosing the value of $\alpha$ can make the trade off between safety margin and delay. The $\alpha$ value has a value for increased speed ($\alpha$ acceleration) and another for reduced speed ($\alpha$ retardation). The $\alpha$ value varies between 0-1. $\alpha=1$ means full smoothing to the next vehicle’s speed, while $\alpha=0$ means no updating at all. In the Netherlands, the $\alpha$ value = 0.2 has mainly been used. This means that the adaptation delay is about $1/\alpha=5$ vehicles, i.e. after 5 vehicles with a new speed.

The AID speed feature of 12 groups (called AID sections), maximum of 3 cross-sections of a maximum of 4 lanes, see figure 3.8, for detected locations is relayed to the outstations. This pattern is converted in the OS to a request for speeds to be shown on its legends (applied autonomously in local mode) or forwarded to the CS (normal mode), which maintains the coherence of the pattern of shown legends as a whole. The requests are determined by means of an action table.

![Figure 3.8. AID sections and their numbering](image)

The calculated smoothed speed values are compared with pre-specified threshold values. Two threshold levels are used for the MCS: 35 and 50km/h. If one of the values subsides its threshold, an AID legend request results. The request is communicated to the CS (normal mode) or applied autonomously (local mode).

The speed feature is compared to threshold values, leading to a classification of the feature in the form of (1/D/0/X) as shown in figure 3.9. For the value 1, request a signalling action, the D region functions as a hysteresis area between a signalling request (1) and the withdrawal of a request (0), while for the value X no classifications are performed.
The next step is to submit a signalling code SS (signalling), NC (no change) or [] (blank) to every possible combination. This is done with an "action table". CS applies the legend rules to the current set of requests and the present legend settings on the gantries on the road, resulting in a new legend pattern. The CS communicates the required legend changes to the outstations that then apply the changes to their respective gantries.

The cycle time of this process is short, about 4-6 seconds, unless there are problems with communication throughout the system. The CS’s polling cycle is timed out after 40 seconds, after which the process starts anew.

The signalling code will result in a speed request, e.g. 50 displayed on a gantry’s matrix. This value is increased with an “AID-offset”, which depends on whether the request is first, second, or third cross section downstream. The AID offset is +0, +20, +20.

### 3.4 MCS EVALUATION STUDIES

In 1999 a field evaluation was made of the Automatic Incident Detection (AID) of the Stockholm and Gothenburg systems, (De Kok, M.L., Van Toorenburg, J.A.C., 1999). Results for the Stockholm system showed that AID errors occurred at random road positions. The main problem was that the AID was switching off too soon. Suggestions to improve the AID function dealt mostly with adjusting or fine-tuning the alpha parameters (see section 3.4.5), which are the smoothing parameters of the speed feature and redefining threshold speeds etc.

#### 3.4.1 User acceptance

There had been complaints from the public about the MCS system, in particular concerning the fact that “50” is displayed in situations where it is actually physically impossible to drive at that speed due to congestion. Vägverket Region Stockholm therefore decided that it was
necessary to investigate the feasibility of alternatives to showing a recommended speed of 50km/h in cases of stationary or slow-moving traffic.

A questionnaire survey was conducted by VTI in autumn 1997 to collect information about drivers’ experiences and their opinion of the MCS and determine whether there were any differences between attitudes for different groups of drivers (Peterson, A. et al., 1998). Questionnaires were sent to 1,965 chosen road-users and 1,018 filled-in questionnaires were returned.

The questionnaire was distributed to almost 2,000 people. The results were as follows:

- About 85% of the drivers had experienced of the system.
- The majority of the road users (8 out of 10) were generally positive to the system.
- The majority felt that they had time to see the most common symbols while driving.
- 25% of these had experienced problematic driving situations, other driver’s behaviour and their own driving situation.
- A comparison between the different driver groups showed that the most obvious differences in experience and perception were between regular commuters and those driving on the stretch in question more sporadically.

In an MSc thesis (Jones, and Stålhammar, J., 1999) evaluated driver comprehension and behaviour in relation to MCS. The purpose of the thesis was to develop a method that could be used to investigate driver behaviour in response to VSL signalling of “recommendation to change lane” and “lane closed”. The focus was on where the drivers changed lanes, i.e. position in relation to the gantries, and how many drivers ignored these messages.

The result of limited field studies in Stockholm and Gothenburg showed that drivers’ respect for the signals was low. Despite the fact that driving past a red cross is an offence, many drivers ignored both red crosses and green arrows. Jones and Stålhammar declared that this implies a lack of information about the system as regards what the symbols means and a lack of respect for the system as a whole.

An attitude survey was carried out by Demoskop2, (Bernsten, C. et al., 2002) with in-depth interviews with 33 people including private drivers, taxi drivers and Trafik Stockholm operators. The aim of the survey was to study how drivers perceived the traffic situation on Essingeleden and at the same time to see what experience they had of MCS on the E4. The results of this study showed that:

- Some of the negative comments were that the signs are incomprehensible and queues can occur as a result of this. MCS is not a solution for peak traffic.
- Positive comments include smooth traffic, easy to close a lane, more information for drivers.

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2 In-depth interviews about Essingeleden, Vägverket Region Stockholm, 1998.
3.4.2 Driver behaviour

A study using the VTI driver simulator was conducted to investigate drivers’ spontaneous reaction to and understanding of MCS signalling (Harms, L., 1997) in more complex signal and traffic environments.

The position during lane change and speed adjustment to what was shown as recommended speed on the matrix signs was of specific interest. Other studied behaviour, which might indicate that the sign were inadequate or not clearly understood, included:

- Unnecessary lane change
- Change to wrong lane
- Driving in a closed lane
- Heavy braking

Results of this study were that the average speed was 71.6 km/h, sometimes higher than the advised speed and sometimes lower. In addition, 75% of drivers changed lane 0-200 m before the signal and 25% after the signal. Misunderstanding of the VMS lane signalling occurs in case of lane changing that happens directly after the signal sequence, where the lane change sign is valid until the next new sequence. A retardation of \( >3\text{m/s}^2 \) was measured. 41 out of a total 591 instances of braking were \( >7\text{m/s}^2 \), half by the same person.

Harms (1997) claims that the speed would be higher in reality and that the simulator cannot correspond to the real circumstances. During the simulator experiment, there was no interaction with other traffic and it is well known that drivers on the E4 are in a highly exposed interaction position.

3.4.3 Traffic performance and Environmental Impacts

The impact of MCS on the southern part of the E4 motorway in Stockholm has been studied by VTI (Carlsson, A., Yahya, M. R., 2004, 2005) along the segment between Bredäng and Eugenia tunnel. This motorway segment was divided into three sections: Bredäng Nyboda, Nyboda-Fredhäll and Fredhäll-Eugenia. The studies were performed twice, in June and December on Monday and Tuesday during morning and evening peak hours and middle of the day. The study considered the impact of the Motorway Control System (MCS) on accessibility and the environment. The study included an analysis of before (2003) and after (2004) implementation of the MCS. Inductive loops for measuring of speeds and traffic flows were installed in each lane along different sections of the motorway. These measurements include passage time, and the speed and type of each passing vehicle. Floating-car measurements were also performed at the same time. The measured speed profiles were used as input to VETO, a simulation program for calculating NOx emissions (g/km). CO2 (kg/km) emission were calculated from fuel consumption.

The surveys were supplemented with measurements of traffic flow and speed from inductive loops and later from the MCS microwave detectors. These detectors were used to collect data of speed and traffic flow. From these measurements it was noticed that in the north driving direction congestion appears in the morning while for the southern driving direction congestion appears in the afternoon.

Table 3.1 summarise the results concerning only the northern driving direction along the segment, Bredäng-Nyboda.
Table 3.1, Effects in the form of fuel consumption per vehicle during rush hours on the Bredäng-Nyboda motorway segment for the north driving direction during June and December, in 2003 and 2004. Source (Carlsson, A. et. al. 2005)

<table>
<thead>
<tr>
<th>Month</th>
<th>Travel speed (km/h)</th>
<th>Travel time (min)</th>
<th>Fuel consumption (litre/mile)</th>
<th>Standard deviation of speed (% increment)</th>
<th>CO2 (kg/km)</th>
<th>NOx (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June-04</td>
<td>20.7</td>
<td>8.5</td>
<td>0.211</td>
<td>100</td>
<td>0.498</td>
<td>0.037</td>
</tr>
<tr>
<td>June-03</td>
<td>29.6</td>
<td>4.9</td>
<td>0.132</td>
<td>30</td>
<td>0.311</td>
<td>-</td>
</tr>
<tr>
<td>December-04</td>
<td>18.8</td>
<td>9.6</td>
<td>0.236</td>
<td>190</td>
<td>0.556</td>
<td>0.106</td>
</tr>
<tr>
<td>December-03</td>
<td>33.9</td>
<td>4.0</td>
<td>0.098</td>
<td>175</td>
<td>0.231</td>
<td>-</td>
</tr>
</tbody>
</table>

Results show low travel speed and long travel times during 2004. Traffic congestion was exceptionally high with a travel speed of 20 km/h. Carlsson, A. (2005) claim that the reason was the increase in traffic flow from Södra Länken downstream that created queues upstream towards Västberga. The increase in congestion leads to an increase in speed variation, which in turn reduce driving comfort. Fuel consumption and emissions follow the same pattern.

3.5 DISCUSSION

The MCS queue warning function is implemented in a reactive manner and no attempt is made to predict the moment of origination of a shockwave, queue, or displacement of the queue tail in advance (Van Toorenburg, J.A.C. et al., 1998). Slow-moving traffic must reach a detection location so that the system reacts. That means that it is impossible for the AID algorithm implemented in the MCS to identify a minor disturbance if it occurs between two detector stations.

The AID cannot identify incidents but their consequences in the form of queue building can be detected. In figure 3.10 below, the detection of the main incident is presented as an event (A) in a time-speed diagram. Because of event A, queue (B) occurs and covers a large area. It is important to protect the tail of the queue during the queue’s lifecycle by the queue warning (the blue band in figure 3.10). In such cases approaching vehicles are warned of queue at (C) by displaying a recommended speed. When the queue gradually dissolves (D) the displayed recommended speed will be inactive (E).

Figure 3.10. Space-time diagram showing detection of an incident contra queue warning, (Source: Transpute, 1999)
The AID algorithm in MCS Stockholm has been in use for almost nine years. However, it is not functioning fully satisfactorily. Complaints have been made about its operation in specific cases but no consensus exists regarding the desired legends with respect to the traffic situation. The fact that the 50 km limit remains activated although the queue is not moving is the complaint that is heard most. The opposite, people are already driving at 100 km/h while the 50 km limit still remains activated, is rarely heard. Drivers find the rapid succession of legends in stop-and-go traffic irritating. Vehicles sometimes join the end of a queue before the gantry signs are activated. During one of my weakly trips by express bus from Stockholm to Linköping, the bus driver was driving in a stop-and-go condition while the recommended speed showed 50 km/h. His comment to the passengers was; “Here we have this intelligent system, which it doesn’t keep up with traffic situation!”.
CHAPTER 4  METHODOLOGY

4.1 BACKGROUND

Uninterrupted traffic characteristics such as flow, density, speed and their relationships need to be analysed, e.g. capacity limitations when a bottleneck situation is created. Plotting of the relationships between all the above-mentioned variables using data collected on the E4 motorway shows that a linear speed-density relationship is not applicable for multi-lane roads as exemplified for the motorway facility E4 in Stockholm in figure 4.1.

Figure 4.1. Relationship between flow, speed, and density obtained from data collected on the E4 motorway in Stockholm.
Different colours in figure 4.1 identify different lanes. Blue identifies the left lane and red and yellow the middle and right lanes respectively. The speed-density plot shows an S-shaped relationship over the entire range of observations. The same figure also illustrates flow-speed and flow-density relationships for the motorway (speed limit 90 km/h). The data were obtained for three lanes over 24 hours of a typical day. Each point represents a one-minute period average.

The flow-density relationship chart in the middle of the figure has a parabolic form, but the congested-flow portion is relatively flat with a tail to the right. In the chart at the bottom of figure 4.1 the speed-flow relationship shows that optimum capacity can be found at a speed around 60 km/h.

During congested traffic conditions the traffic flow reaches capacity at speeds of 50-60 km/h. The traffic flow is then very sensitive to disturbance, which may cause breakdown of traffic flow and queues, which in turn may take a long time to clear. Such cases can be seen in the lower portion of the curve in figure 4.2. If the speed of the undisturbed traffic flow could be reduced the risk of breakdown of traffic flow and capacity will also be reduced.

![Speed-Traffic flow relationship on three lanes motorway E4-Stockholm](image)

**Figure 4.2. Speed-flow relationship for three lanes of the E4 motorway in Stockholm.**

The relationships between speed and flow and density and flow are important as they are utilized as the basis for motorway traffic control and management, which aims to keep the density below the optimum density value when demand exceeds capacity.

There is a need to gain a better understanding of motorway operation under congested conditions in order to identify critical density and critical speed. This is necessary in order to know when to apply control measures to lower speed limits before the critical speed is reached, which will lead to better utilization of the infrastructure.
4.2 APPROACH

On congested motorways, shockwaves are normally frequent and cause “stop-and-go” waves, in which vehicles can only travel at reduced speed or come to a complete standstill for periods of time. Furthermore, congestion increases the amount of interaction between vehicles and may leads to a large number of lane changes in very short gaps. The aim of implementing the MCS was to improve traffic performance and safety through VSL to reduce the impact of congestion. The following approach was used to assess the effectiveness of VSL and provide a better understanding about factors that impact it, see figure 4.3.

![Diagram](image)

Figure 4.3. Speed-flow relationship for three lanes over one day.

4.2.1 Field studies

For field studies comprehensive data were collected for before and after VSL including the following, (Figure 4.4):

- Video based field study of driver behaviour and VSL impact covering 500 meter segment of the E4 motorway with a VSL gantry. The study included tracking of individual vehicles before and after implementation of VSL in order to capture speed, headway and lane changing manoeuvres. The data was also used to obtain traffic flow, lane distribution, and speed and headway distribution with and without VSL.

- MCS detector and AID data based field study of VSL impacts for analysis of speed, flow and density variables and their relationships.

- Mobile field study of driver behaviour before and after implementation of VSL (MCS) on 10 km segment of the E4 with 14 VSL gantries. The observations included vehicle speed, time headway, acceleration and deceleration. The field data covered different
traffic conditions including restrained and free traffic flow conditions with and without displayed recommended speed messages (VSL).

![Applied methodology framework for the empirical study](image)

Some of the collected data from the empirical study was subsequently used to calibrate and validate a micro simulation model, which was be used to assess the impacts of the VSL.

### 4.2.2 Simulation studies

MCS is a dynamic system, and its impacts on driver behaviour and traffic performance is complex and difficult to study in the field due to the difficulty of controlling unexpected traffic conditions (e.g. weather conditions, travel demand, incidents). A study was therefore also performed using a microscopic traffic simulation model. With a microscopic simulation model of the system it is possible to conduct controlled experiments to determine the impacts of the system on traffic performance. Furthermore, simulation can be used to study alternative solutions and strategies to achieve more effective traffic management. The following steps are required to accomplish this, see also figure 4.5. The simulation study had the following objectives:

- Evaluate the impact of the VSL on traffic performance during recurring congestion conditions.

- Evaluate the impact of the VSL on traffic performance during incident conditions.

- Evaluate the impact of the VSL integrated with ramp metering under recurring congestion.
The applied methodology for execution of the research strategy includes the following stages:

- Calibration, validation and application of the simulation model for VSL impact assessment
- Implementation of VSL functionality, (AID algorithm) and driver behaviour characteristics in a microscopic simulation model
- Assessment of the simulation model for studying the impacts of the VSL on traffic process
- Assessment of the simulation model for studying application of control of measure as VSL, ramp metering and combination of two strategies on traffic process

4.2.3 Measures and indicators

The detailed data collection aimed at measuring the following indicators of effectives:

- Traffic performance, level of service indicators:
  - Traffic flow distribution by vehicle type and lane
  - Mean speed and speed distribution
  - Mean headway and headway distribution
  - Travel time
- **Driver behaviour**

The aim of the mobile survey is to compile detailed driver behaviour data and the interaction of adjacent vehicles under different traffic conditions, (low and high traffic flow respectively) with and without VMS activation. This data will later constitute input data for traffic behaviour in the simulation model taking the following factors into consideration.

- Vehicle speed
- Driver behaviour during lane change (acceleration, headway)
- Driver behaviour during VSL signalling (acceleration/deceleration)

- **Safety indicators:**

- Number of accidents and secondary incidents (historical incident data)

### 4.3 DESCRIPTION OF THE TEST SITE

The studied stretch (7 km) is part of an extension of the MCS from the Eugenia tunnel north of the inner city to Bredäng in the south. The stretch starts at the Bredäng interchange and terminates at the Västertorp interchange and includes four on-ramps and two off-ramps. The stretch has three lanes (3.5m/lane) per direction of travel with a variable speed limit of 90 km/h for the northbound driving direction for 2.8 km and 70 km/h for the remainder.

Four bridges cross the studied stretch: one bridge for motorised vehicles, bikes and pedestrians, two for bikes and pedestrians, and one for a combination of pedestrians, bikes and trams, see figure 4.6. The bridges were used as vantage points for video camcorders covering the whole studied motorway stretch in both directions of travel.

*Figure 4.6. The studied stretch of motorway.*
CHAPTER 5  STATIONARY FIELD STUDIES

5.1 INTRODUCTION

Field data collection (empirical studies) were carried out as before and after studies with respect to the application of VSL with the purpose of analysing traffic characteristics such as traffic flow, speed and headway. The studies included video stationary data collection on 500 meter segment of the motorway and MCS data including detector data, AID alarms and VSL signalling status.

Previous studies on the same segment but with different purposes (Carlsson, A., Yahya, M. R., 1998; Carlsson, A. et al., 1999; Carlsson, A. et al., 2000; Carlsson, A. et al., 2001, 2002, 2003, 2004 and 2005) were used as a basis for choosing a section of the E4 south of Stockholm as the study site. Heavy congestion during three hours occurs daily in the northbound direction towards the city centre in the morning peak periods.

Two surveys were performed, a “before” and an “after” survey covering the same stretch. During the “before” study, which was executed on 25th May 2004, the MCS was implemented without displaying any recommended Variable Speed Limits (VSL) to the drivers. On 28th May, the MCS system was in operation and displayed recommended speeds when triggered by Automatic Incident Detection (AID) alarms. The “after” study was performed four months later on 30th September 2004 in order to capture the system’s performance with VSL fully activated when required.

5.2 DATA COLLECTION AND PROCESSING

This study included a stationary data collection, MCS detector data and video recordings of individual driver behaviour with and without the influence of activated lane signals of different types. The reaction of a driver to the presence of an external stimulus was also an important purpose in order to capture an input to microscopic simulation models. The main elements of this behaviour are traffic composition, vehicle distribution, speed, time headway and lane-change. The data collection was designed to capture these characteristics. The different methods applied to collect the needed data are described below.

Stationary data collection using video camcorders.

On motorways with very high traffic volume it is not possible, for safety reasons, to lay out temporary surface-mounted detectors, or go near the boundary to make other measurements. To gain more insight into the behaviour of drivers during congested traffic conditions, a very detailed data collection is required. For this purpose, video recording from elevated positions was chosen, as described above. Real-life data were recorded on video to provide additional data at different locations. VCRS were placed on different bridges. Two of the cameras were placed on a 15 meter mast mounted on a bridge over the E4 motorway. A bike and pedestrian bridge located between gantries 65.815 and 65.420 was chosen to locate two remote control videocameras mounted on a 15 meter mast on Tram Bridge without disturbing the traffic flow. The cameras were aimed in both driving directions, see figure 5.1.
The two mast-mounted cameras see figure 5.2, covered almost 250 meters of the motorway in each direction. The maximum recommended distance is 300 meters (Kronborg, P., 1998). The cameras were aimed at departing and arriving traffic to capture the traffic flow. Other single cameras (4 sets) were located separately in strategic locations overlooking the motorway. The cameras and their operators were concealed from the direct view of the drivers being measured. The traffic was filmed with 8 mm format video cameras.

In order to capture different traffic conditions, Traffic was videotaped for 12 hours each day, in both driving directions, during the morning, midday, and afternoon peak periods for several days.
The surveys included the following traffic characteristics, which were observed and collected for each lane:

- Traffic flow on the mainline and also on the on and off ramps.
- Traffic flow composition and distribution
- Headway and headway distribution (headway defined as the time between the passage of the front axle of the leading vehicle and the front axle of the following vehicle).
- Spot speed and speed distribution
- Lane distribution and lane changes frequency
- Appearance of congestion.

**MCS surveillance system data collection**

Data from the MCS system are collected by microwave detectors mounted on each gantry over each lane. Data provided by the MCS microwave detectors is aggregated by outstations in the field before it is transmitted to the traffic control centre. The resulting information includes aggregated traffic flow and the average speed for each lane per minute. In addition, MCS logs of AID alarms and the time of VSL activation and recommended speed level for each lane were used to support the video data analysis regarding the impacts of the system.

Table 5.1 summarizes the scope of the “before” and “after” VSL surveys.
<table>
<thead>
<tr>
<th>Measurement Site</th>
<th>Date and time period</th>
<th>Weather condition</th>
<th>Type of measurement</th>
<th>Measurements equipment</th>
<th>Camera placement/Stretch location</th>
<th>Motorway characteristics</th>
<th>Type of data collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Södertäljevägen</td>
<td>2004/09/29 &amp; 2005/10/28-31</td>
<td>Cloudy the whole day. Little rain early in the morning and heavy rain in the evening. The wind was between north to southwest in the evening. 5.4 to 10.3 degrees Celsius</td>
<td>Travel time surveys</td>
<td>Car following survey in peak traffic period for one hour.</td>
<td>A distance of 1.150 km - On bridge at Västertorp interchange - At Pedestrian-bike bridge at Tram bridge - On bridge at Brodäng interchange</td>
<td>3 lanes + 3 lanes in different driving directions</td>
<td>Speed profile, headway, acceleration, passage time</td>
</tr>
<tr>
<td>Södertäljevägen Stretch between Västertorp and Brodäng</td>
<td>2004/07/30 &amp; 2005/10/28-31</td>
<td>Cloudless sky the whole day. Wind between north and west. 6.0 to 14.6 degree Celsius</td>
<td>Travel time surveys</td>
<td>Car following survey in peak traffic period for one hour.</td>
<td>A distance of 1.450 km between Västerberga and Skåholmsten interchanges</td>
<td>3 lanes + 3 lanes in different driving directions</td>
<td>Speed profile, headway, acceleration, passage time</td>
</tr>
<tr>
<td>Södertäljevägen Stretch between Västertorp and Brodäng</td>
<td>2004/07/30 &amp; 2005/10/28-31</td>
<td>Cloudless sky the whole day. Wind between north and west. 6.0 to 14.6 degree Celsius</td>
<td>Travel time surveys</td>
<td>Car following survey in peak traffic period for one hour.</td>
<td>A distance of 1.150 km - On bridge at Västertorp interchange - At Pedestrian-bike bridge at Tram bridge - On bridge at Brodäng interchange</td>
<td>3 lanes + 3 lanes in different driving directions</td>
<td>Speed profile, headway, acceleration, passage time</td>
</tr>
<tr>
<td>Södertäljevägen North and south driving direction</td>
<td>5 days from 2004/07/30 &amp; 2005/10/28-31 07:00 to 09:00, 15:30-17:30</td>
<td>Cloudless sky the whole day. Wind between north and west. 6.0 to 14.6 degree Celsius</td>
<td>Travel time surveys</td>
<td>Car following survey in peak traffic period for one hour.</td>
<td>A distance of 1.450 km between Västerberga and Skåholmsten interchanges</td>
<td>3 lanes + 3 lanes in different driving directions</td>
<td>Speed profile, headway, acceleration, passage time</td>
</tr>
</tbody>
</table>

Table 5.1 Surveys conducted in empirical study.
5.3 DATA PROCESSING METHOD

Playback of video recording

The aim of the data processing was to record speed pattern, headway, and lane selection for individual drivers. To capture traffic behaviour on a microscopic level, the collected data and the videotapes were processed using Semi-Automatic Video Analysis Version 4.4 (SAVA), a video analyzer program developed at KTH (Archer, J., 2003). The SAVA program has been designed to interpret the information from digital films recorded in Digital Audio Video Interleaved (*.avi) format. All semi-automatic film analysis is time-consuming and tedious work, but the results can provide a great deal more information than that collected by rubber tube based pneumatic detectors connected to a logger.

The main function of the SAVA program involves the use of virtual lines, which are created in a manner analogous to inductive loop detectors on the screen by the user to log event times for road-users (vehicles, cyclists and pedestrians). To extract data from the video image, the vehicles are manually detected each time one reaches a virtual line. The event can be registered by clicking either on the line representing the virtual line or the number box in the application. This will result in an event-time entry into a log file that consists of the current film time, the virtual line number, the road-user type and the road-user identification number. A screenshot from the SAVA device is shown in figure 5.3.

All passing vehicles are detected through determination of their front and back axle passages in the video picture. Using this technique, vehicle type, time-space trajectories, speed and headway can be determined as well as lane occupancy and the rate of lane changes. The performance of this method is 100% of the vehicles detected. When the vehicles are detected, their positions, type, speed, time headway, and lane change can be calculated. The aim of the data reduction is to record speed pattern, headway, and lane selection for individual drivers.

Figure 5.3. Screenshot image from the SAVA device.
MCS data processing

Data provided by the MCS microwave detectors is aggregated by outstations in the field before being transmitted to the traffic control centre. The resulting information includes aggregated traffic flows and the average speeds for all lanes per minute. Furthermore, the system records AID alarms and the time of activation and deactivation of the recommended displayed speed signs and lane closure signals. Figure 5.4 below shows the plotted data for one gantry over a period of two hours. The data include average speed, traffic flow per minute and the displayed recommended speed (VSL).

![Traffic flow, average speed and displayed recommended speed](image)

*Figure 5.4. Detected traffic flow, average speed, and displayed recommended speed.*

This figure shows the speed profile, traffic flow variation and the pattern of the displayed VSL. During the period between 08:20 and 08:45 the displayed speed varies between 50 km/h and 70 km/h while the drivers might be travelling at speeds of only just below 17 km/h and 35 km/h.

Comparison of Video data and MCS data

Figure 5.5, shows the comparison of MCS detectors and video recordings including average speed, average headway and traffic flow data for the middle lane. The MCS detectors showed a 4% higher speed than data obtained by video recording. The results showed that MCS detected a 6.2% shorter time headway compared with video data. Similar comparisons were made for traffic flow data. MCS under-counted traffic flow by almost 1% compared to video data.

For the purposes of this study, the traffic behaviour and traffic process are investigated during VSL OFF and VSL ON. Representative data are collected in the same place and over the same periods for VSL OFF and VSL ON.
Figure 5.5. A comparison of average speed, average headway and traffic flow data obtained by MCS detectors and video recording.
5.4 EVALUATION BASED ON A SINGLE MEASURE OF PERFORMANCE

5.4.1 Introduction

Data for the morning peak period (07:00-09:00) were collected on 25\textsuperscript{th} May 2004 (VSL OFF) and on 30\textsuperscript{th} September 2004 (VSL ON), see figure 5.6. Data including individual traffic characteristics for three lanes were plotted and analyzed to obtain traffic flow and composition, lane distribution, speed and time headway distributions and lane changes.

![Figure 5.6. Vehicle speed (km/h) during morning peak traffic during VSL OFF (upper) and VSL ON (lower)](image)

Traffic flow characteristics vary dynamically and each traffic situation is in some way unique. Different types of events occur, which are sometimes local and may sometimes cover several
kilometres due to shockwaves when traffic demand exceeds capacity. This can be observed as a sharp decrease in speed for the case VSL OFF in figure 5.7 upper, and with VSL ON in figure 5.7 lower.

It is difficult to find comparable time periods with VSL ON and VSL OFF due the random occurrence and character of incidents triggering the display of recommended speed signs.

However, the following time periods were chosen to exemplify typical traffic characteristics for such conditions (see figure XX) as documented in the following sections:

- VSL OFF between 07:34- 08:10
- VSL ON between 07:17- 08:01

Difficulties occur when studying the impact of the VSL, because in this kind of environment it is not easy to control the many other factors that could influence speed during VSL ON (besides the VSL).

However during VSL OFF a period of time between 7:34- 8:10 was chosen while during VSL ON a period of time between 7:17- 8:01 was chosen (figure 4) to study traffic characteristics for these periods.

### 5.4.2 Traffic flow and lane distribution

The observed traffic flow distribution along the motorway segment during the chosen studied periods for each of the three lanes during VSL OFF and VSL ON is shown in table 5.2.

<table>
<thead>
<tr>
<th>VSL-Status</th>
<th>Traffic flow (v/h)</th>
<th>Left lane</th>
<th>Middle lane</th>
<th>Right lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSL OFF</td>
<td>3778</td>
<td>0.38</td>
<td>0.34</td>
<td>0.28</td>
</tr>
<tr>
<td>VSL ON</td>
<td>4505</td>
<td>0.36</td>
<td>0.33</td>
<td>0.31</td>
</tr>
</tbody>
</table>

*Table 5.2. Lane distribution of traffic flow.*

During the morning rush hours it was noticed that, drivers preferred the fast (i.e. the left-most) lane, leaving the other lanes under-occupied. Similar results have been reported by Smulders (1990).

Average speed for each lane within the chosen time periods for cases of VSL OFF and VSL ON are shown in table 5.3 and illustrated in figure 5.7. Results from the studied examples show that speeds increased in all lanes during application of VSL. A sharp decrease in speed and headway variance in all lanes was also observed.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Lane</th>
<th>Average speed (km/h)</th>
<th>Speed Variance</th>
<th>Average headway (sec.)</th>
<th>Headway Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSL OFF</td>
<td>Left lane</td>
<td>48.44</td>
<td>180.64</td>
<td>2.10</td>
<td>0.94</td>
</tr>
<tr>
<td>VSL ON</td>
<td>Left lane</td>
<td>51.84</td>
<td>72.34</td>
<td>2.12</td>
<td>0.66</td>
</tr>
<tr>
<td>VSL OFF</td>
<td>Middle lane</td>
<td>43.81</td>
<td>88.12</td>
<td>2.33</td>
<td>2.42</td>
</tr>
<tr>
<td>VSL ON</td>
<td>Middle lane</td>
<td>46.01</td>
<td>36.43</td>
<td>2.42</td>
<td>1.44</td>
</tr>
<tr>
<td>VSL OFF</td>
<td>Right lane</td>
<td>43.81</td>
<td>81.59</td>
<td>2.47</td>
<td>2.67</td>
</tr>
<tr>
<td>VSL ON</td>
<td>Right lane</td>
<td>46.26</td>
<td>25.27</td>
<td>2.67</td>
<td>1.81</td>
</tr>
</tbody>
</table>

*Table 5.3. Average speed and headway and speed and headway variance for the studied VSL OFF and VSL ON time periods.*
5.4.3 Lane Changes

Lane changes were observed through video recordings over a 200 meter segment. Figure 5.8 shows the results regarding the frequency of lane changes and their distribution for the morning peak traffic period (07:00 – 09:00).
During VSL OFF 4% of the vehicles changed lane. During periods with VSL ON the rate of lane changing was reduced by 50%. Most lane changes during periods with VSL OFF occurred from the middle lane to the left lane. The reduction in speed variance combined with an improvement in lane utilization may have contributed to the need to change lane.

### 5.4.4 Analysis of MCS functionality

The MCS detector data for 10 consecutive gantries over 14 days were used to study the system’s functionality. Data for all gantries in sequence were plotted and the traffic situations in response to the VSL display of recommended speeds (VSL ON) were followed. A representative example of three gantries in sequence is shown in figure 5.9. The figure illustrates average speed per minute and the displayed recommended speed on the VSL panels, during the morning peak periods between 7.00-9.00 a.m. The figure shows vehicle’s actual speed in relation to the recommended speeds displayed on the studied sequence of gantries.
Along the section with a posted speed of 90km/h the detection of low speed downstream resulted in recommended low speed being displayed almost 2 km upstream. By illustrating the average speed and displayed recommended speed at three gantries in sequence we can study how these variables changed for different gantries. Such changes are shown in figure 5.11, where three gantries were chosen. In this case an average speed of <35km/h was detected at the upper gantry.

At the lower gantry the drivers were warned of a downstream queue by a lower recommended speed (70km/h) being display at 8:00 am. The detected average speed at this moment was almost 90 km/h, i.e. there was no response from drivers to follow the recommended speed. If the drivers had reduced their speed, the downstream queue at gantry 1 would probably have been less severe, and the risk of encountering a queue situation further downstream would have decreased. This behaviour was often observed at all 10 gantries over the 14-days period. In other cases the average speed was much lower than the recommended speed, probably because of the dense traffic.
Collected MCS detector data were used to investigate the number of vehicles which kept the recommended speed in order to obtain the share of drivers who followed the recommended speed. The results from these measurements showed that 74% of the drivers drove faster than the recommended speed.

Both the time and duration of the recommended speed display and the intermission of very short duration between activations can be measured. The existing problems with MCS operation are related to specific cases; no consensus exists regarding desired VSL legends with respect to different traffic situations. The displayed recommended speed during congested conditions was normally higher than could be maintained, which could confuse drivers.

### 5.4.5 Traffic accidents

The impact of VSL on the occurrence of traffic incidents and accidents on the E4 motorway was studied using data from STRADA, the Swedish national information system for registration of such events in the road transport system. Data about accidents occurring on Södertäljevägen was collected and studied comprehensively. These data were classified by year and covered periods before and after the application of VSL. VSL was applied in September 2004. Accidents occurring during 2004 were classified in 2000-2004A for (VSL OFF) and 2004B-2007 for VSL ON, see figure 5.10.

![Figure 5.10. The number of different type of accident that occurred on the southern part of the E4 motorway](image)

The result show that most of the accidents were rear-ends collisions. More accidents occurred during the evening peak hours. On the studied segment of Södertäljevägen, two fatalities occurred (2002 and 2005) during the studied seven years. Both accidents happened during evening rush hour and were an overtaking accident and a rear-end collision.

The results show that during periods with VSL ON there were very few overtaking accidents. Regarding rear-end collisions and single-vehicle accidents the results indicate that the number of this type of accidents were 27% and 42% respectively during VSL ON. However these results are not significant due to the limited data available and the short time period.
Discussion

Comprehensive traffic variable data (traffic flow distribution, mean speed, mean headway, etc.) were collected during peak periods for one day before and one day after implementation of VSL in order to analyze the impact of VSL operation on traffic behavior and performance. However, the traffic conditions and the occurrence of incidents vary dynamically and making each traffic situation unique. It was thus not possible to identify “before” and “after” time periods with similar traffic conditions to analyses and draw significant conclusions with regard to VSL impacts. Recommended speeds are displayed by VSL when low speed is detected downstream with the intention of warning on-coming drivers, but it cannot be verified to what extent approaching drivers react to these signs or by observing queuing conditions downstream. The analysis of VSL impacts based on the empirical data was therefore limited to selected time periods exemplifying typical conditions. The empirical was therefore instead mainly used to enable calibration and validation of a simulation model developed for the purpose of conducting controlled experiments of VSL impacts.

To avoid the limitation of the available data, the empirical data collected from the MCS system was used to assess the impacts of advisory VSL using a statistical methodology for the comparison of traffic conditions before and after VSL implementation based on the underlying speed-density relationships. This is the subject of the following section.
5.5 EVALUATION BASED ON MULTI-DIMENSIONAL MEASURES OF PERFORMANCE

5.5.1 Introduction

The analysis of field data to evaluate the performance of the system was focused on comparing individual Measures of Performance (MOPs) at specific locations. MOPs used include traffic flow, speed and headway distribution. It was found that the VSL contributed to more even traffic flow distribution between lanes. However, no definitive conclusions could be drawn regarding the overall effectiveness and impact of VSL on the operations of E4.

The problem with analysis based on field data collection is that it is very difficult to isolate the impact of other factors that may contribute to whatever changes are observed. In order to minimize this problem in this section we focus on assessing the impact of advisory VSL using a statistical methodology for the comparison of traffic conditions before and after the implementation of VSL based on the underlying speed-density relationships.

5.5.2 Evaluation methodology

The method used in this study is similarly motivated as in Papageorgiou (2008) and is based on an approach first reported in Toledo and Koutsopoulos (2004) for the validation of traffic simulation models through the comparison of simulated and actual data. Toledo and Koutsopoulos (2004) suggest the use of single-valued (e.g. speed) and multivariate (e.g. speed and density) measures of performance (MOP) for the validation of simulation models. Multivariate approaches, although desirable, are difficult to implement, unless a lot of data is available. Even if data is available, potential statistical tests may violate underlying assumptions, or be too loose to be useful. In response to that, Toledo and Koutsopoulos, (2004) propose the use of meta-models to compare results from a simulation model to actual observations. Such meta-models capture the underlying relationship between two (important) traffic variables and hence the evaluation can be based on a statistical test of whether or not the two functional forms are the same. This approach requires less data to be applied and aims at testing the structural differences in traffic conditions, as captured by the relationship between these variables.

The same methodology can also be used to test whether the introduction of VSL resulted in any statistically significant changes in aggregate traffic behaviour. A natural selection of relationships to be tested comprises those related to the fundamental diagram in general traffic stream models for the facility of interest. Such models, for example the relationship between speed and density, are representative of the characteristics of a given facility, and can be viewed as the identity of the facility. Speed-density relationships, for example, capture the behaviour of a facility under prevailing traffic, control, and weather conditions. Such relationships can be developed using speed/density data from before and after the implementation of VSL. Assuming the data are collected under similar conditions in terms of weather and traffic composition, the relationship should be the same, unless the implementation of VSL brings about structural changes in the way traffic dynamics develop and the facility behaves from a traffic point of view.

The proposed methodology uses traffic data before and after the implementation of VSL and proceeds in two steps:
1. Specify and estimate a traffic stream model that captures the underlying relationships (consistent with traffic flow theories) between the chosen traffic variables, for example speed \( V \) and density \( K \), and estimate its parameters using regression analysis and the corresponding data from before and after the VSL implementation.

2. Use statistical tests to test for the equality of coefficients across the two meta-models (corresponding to before and after conditions).

The equality of the coefficients of the models is tested with the null hypothesis \( H_0: \beta_{\text{before}} = \beta_{\text{after}} \) against \( H_1: \beta_{\text{before}} \neq \beta_{\text{after}} \), using a generalized F-test. The test uses two models: restricted (R) and unrestricted (UR). The restricted model, which forces the equality of parameters of the two meta-models, is estimated with the combined dataset (both before and after VSL). The unrestricted model is the combination of two separate models, one estimated with the before data, the other with the after VSL data.

Let \( \text{SSE}^{\text{before}} \) be the sum of square residuals when the model is calibrated with the before data, \( \text{SSE}^{\text{after}} \) the sum of square residuals with the model calibrated using the after data, and \( \text{SSE}^{\text{before} + \text{after}} \) the sum of the squared residuals when the model is estimated with the combined data (pooled before and after data). Then the test statistic \( F \) is calculated by:

\[
F_{K, N^{\text{before}} + N^{\text{after}} - 2K} = \frac{(\text{SSE}^{\text{R}} - \text{SSE}^{\text{UR}}) / K}{\text{SSE}^{\text{UR}} / (N^{\text{before}} + N^{\text{after}} - 2K)}
\]

\( \text{SSE}^{\text{R}} \) and \( \text{SSE}^{\text{UR}} \) are the sums of the squared residuals of the restricted and unrestricted models respectively, defined as:

- \( \text{SSE}^{\text{R}} = \text{SSE}^{\text{before} + \text{after}} \)
- \( \text{SSE}^{\text{UR}} = \text{SSE}^{\text{before}} + \text{SSE}^{\text{after}} \)

\( N^{\text{before}}, N^{\text{after}} \) are the number of observations in the before and after VSL data

\( K \) is the number of parameters in the model.

The value of the test statistic \( F_{K, N^{\text{before}} + N^{\text{after}} - 2K} \) is compared against the corresponding critical value for the selected significance level in order to draw conclusions regarding the null hypothesis. The proposed method is very flexible and may also overcome issues related to limited data availability.

For this case study the same section of the motorway shown in Figure 5.1 was used to apply the methodology presented above. For this study data were collected from the MCS detectors at the gantry locations indicated in Figure 5.11. The data include average speed and traffic flows in 5 minute intervals.

![Figure 5.11. E4 motorway section at Södertäljevägen.](image)

For the before VSL scenario data from only one day, 25\textsuperscript{th} May 2004, were available. After the start of application of VSL scenario data from 30\textsuperscript{th}, September 2005 (soon after the
introduction of the VSL) were used. Data were also collected during May 2005, covering days 10, 12, 18, 26 and 31. The after VSL data sets represent two different points in the operations of the system: immediately after VSL and a few months later when the system is more mature and the drivers more familiar with its operation (and effectiveness) and having adapted their driving behaviour. All days (before and after) had similar weather conditions (dry, no rain) Data were collected from 6 am to 7 pm.

Figure 5.12 shows the variability of speed over time for the various days for which data is available. During the evening peak period (outbound) there is a significant drop in speeds, consistently through all days, indicating severe congestion.

![Average speeds for different days during VSL OFF and VSL ON](image)

**Figure 5.12. Speed over time for various days**

### 5.5.3 Results

The methodology discussed in the previous section was used to evaluate the impact of VSL on the operation of the E4 motorway. In the first step of the methodology candidate traffic stream models representing the relationship between important variables were selected and estimated. For the purpose of this study speed-density models, were developed to capture the underlying traffic characteristics in the section of interest.

As mentioned in section 2.1 traffic stream models were first introduced as long ago as 1935 (Greenshield, 1935). The initial models were single regime models using the same functional form to describe the relationship between speed and density under all traffic conditions. Edie, L. C, (1961), proposed the use of multi-regime models to achieve better fit to field data. Multi-regime models use different functional forms to describe the relationship between speed and density under different congestion levels.

In this study, following Edie, L. C, (1961), a two-regime model was assumed and estimated using the before, after, and combined (pooled) data.

\[
V = \begin{cases} 
  a_1 + a_2 K + a_3 K^2 & \text{if } k \leq 30 \text{veh/km/lane} \\
  b_1 + b_2 K + b_3 K^2 & \text{if } k \geq 30 \text{veh/km/lane} 
\end{cases}
\]

where,

- **V**: speed (km/hr)
- **K**: traffic density (veh/km/lane)
- \(a_i, b_i\): parameters
The above speed-density relationships were estimated for each of the three lanes individually. Figures 5.13-5.15 illustrate the speed-density relationships for the three lanes that resulted from the regression analysis and the corresponding observations.

Figure 5.13. Speed-density relationship, left lane
Figure 5.14. Speed-density relationship, middle lane
Tables 5.4 (densities less than 30 veh/km/lane) and 5.5 (densities more than 30 veh/km/lane) summarize the results of the regression analysis for both the restricted and unrestricted
models separately for each lane. The values of the F-statistic for each case are also reported. In the case of densities less than 30 veh/km/lane the critical value of the F-statistic for $(N_{\text{Before}}+N_{\text{After}}-2K) > 100$ degrees of freedom at the 95% confidence level is 8.53.

<table>
<thead>
<tr>
<th>Densities &lt;30</th>
<th>SSE (Left lane)</th>
<th>Degree of freedom</th>
<th>SSE (Middle lane)</th>
<th>Degree of freedom</th>
<th>SSE (Right lane)</th>
<th>Degree of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Apr 04</td>
<td>1188</td>
<td>119</td>
<td>714</td>
<td>118</td>
<td>526</td>
<td>126</td>
</tr>
<tr>
<td>30 Apr 04</td>
<td>577</td>
<td>110</td>
<td>662</td>
<td>111</td>
<td>362</td>
<td>109</td>
</tr>
<tr>
<td>Combined case A</td>
<td>2023</td>
<td>232</td>
<td>1535</td>
<td>231</td>
<td>1020</td>
<td>232</td>
</tr>
<tr>
<td>25 May 04</td>
<td>1188</td>
<td>119</td>
<td>714</td>
<td>119</td>
<td>536</td>
<td>120</td>
</tr>
<tr>
<td>10, 15, 31 May &amp; 2 Jun 2005</td>
<td>5360</td>
<td>616</td>
<td>4292</td>
<td>616</td>
<td>2449</td>
<td>616</td>
</tr>
<tr>
<td>Combined case B</td>
<td>6193</td>
<td>820</td>
<td>5055</td>
<td>820</td>
<td>3341</td>
<td>818</td>
</tr>
</tbody>
</table>

Table 5.4. Statistics for densities <30 veh/km/lane

The results from before and immediately after the application of the VSL show that the null hypothesis that the speed-density relationships are the same before and after VSL cannot be rejected for any lanes. Similarly, the results from before and several months after application of the VSL show that the null hypothesis that the speed-density relationships are the same before and after VSL cannot be rejected for any lanes. These conclusions were expected since in this regime (stable conditions) the observed speeds are between 70 and 100 km/h and hence the VSL system typically provides no speed recommendation.

In the case of densities greater than 30 veh/km/lane congestion levels are high and low speeds are observed. Consequently in this range the VSL is expected to be triggered and provide speed recommendations to motorists. However, the results of the regression analysis and hypothesis testing, summarized in Table 5.5, indicate that before and (directly) after application of the VSL, the null hypothesis that the speed-density relationships are the same before and after VSL cannot be rejected for all lanes. The results of the before and few months after application of the VSL again show that the null hypothesis that the speed-density relationships are the same before and after VSL cannot be rejected for all lanes.
Table 5.5. Statistics for densities >30veh/km/lane.

<table>
<thead>
<tr>
<th>Densities &gt;30</th>
<th>SSE (Left lane)</th>
<th>Degree of Freedom</th>
<th>SSE (Middle lane)</th>
<th>Degree of Freedom</th>
<th>SSE (Right lane)</th>
<th>Degree of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 May 04</td>
<td>129</td>
<td>29</td>
<td>96</td>
<td>28</td>
<td>106</td>
<td>30</td>
</tr>
<tr>
<td>30 Sep 04</td>
<td>201</td>
<td>39</td>
<td>171</td>
<td>38</td>
<td>183</td>
<td>30</td>
</tr>
<tr>
<td>Combined case A</td>
<td>395</td>
<td>71</td>
<td>272</td>
<td>70</td>
<td>410</td>
<td>72</td>
</tr>
<tr>
<td>14, 15, 16, 17 May &amp; 7 Jun 2005</td>
<td>338.4</td>
<td>136</td>
<td>1655</td>
<td>137</td>
<td>1525</td>
<td>136</td>
</tr>
<tr>
<td>Combined case B</td>
<td>38333</td>
<td>168</td>
<td>1969</td>
<td>169</td>
<td>2224</td>
<td>169</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case A</th>
<th>Case A</th>
<th>Case A</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSE$^a$</td>
<td>375</td>
<td>222</td>
</tr>
<tr>
<td>R$^2$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>F</td>
<td>2.01</td>
<td>0.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case B</th>
<th>Case B</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSE$^a$</td>
<td>3333</td>
<td>1968</td>
</tr>
<tr>
<td>R$^2$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>F</td>
<td>0.93</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The methodology discussed in this section was used to evaluate the impact of VSL on traffic condition by using speed-density models to capture the underlying traffic characteristics in the section of interest. The results indicate that VSL did not have any significant impact on traffic conditions, neither immediately after its implementation nor several months later. The same data used in this section was used again to create flow-density models, see figure 5.16. The impact of VSL on flow-density relationship was investigated qualitatively. The results illustrated in figure 5.16 tend to support recent conjecture by Papagiorgiou et.al. (2008), about the impact of VSL on the critical occupancy. They also tend to indicate a small increase in capacity, but more detailed analysis, including all gantries is needed.
Discussion

Variable message signs are implemented as a means of improving traffic conditions on motorways. Previous studies have assessed the effectiveness of VSL under various conditions and operating strategies. In particular a recent study (Papageorgiou, M. 2008) of a European implementation of mandatory VSL has shown that VSL has the potential to increase the critical occupancy. Results concerning the impact on capacity were not conclusive, although other studies show an increase in capacity due to VSL.

In this section a statistical method for the evaluation of the impacts of VSL on traffic operations of a facility was presented. The method is based on the estimation of traffic stream models using data before and after the implementation of the VSL. A case study, with data from the E4 motorway in Stockholm, was conducted. The implemented VSL uses a speed-based logic and is advisory. The results indicate that VSL did not have any significant impact on traffic conditions, neither immediately after its implementation nor several months later.

The results contradict the conclusions reached in (Papageorgiou, M. 2008). An important reason might be that the displayed VSL in Stockholm is recommended and not mandatory.
CHAPTER 6 MOBILE STUDY

The success of dynamic motorway traffic management depends to a large extent on how the drivers respond to the displayed Variable Speed limits (VSL), and their interaction with other vehicles. Traffic characteristics such as speed, headway and lane distribution are normally detected and processed by surveillance systems. This information can then be used as the basis for the control as well as for information to the road users regarding traffic conditions. Many studies of motorway driver behavior have been made based on interviews considering psychological indicators. This chapter documents a study using instrumented vehicle measurements to obtain observations of driver response to displayed VSL.

The scope of the study covered individual driver behaviour obtained from the mobile measurements carried out before and after implementation of the VSL. The observations included vehicle speed, acceleration and deceleration. The field data covered different traffic conditions, restrained and free traffic flow conditions, with and without displayed recommended Variable Speed Limit (VSL).

The objective of this study was to determine driver behaviour and response to the (VSL) for selected motorway segments, and to apply these results to the analysis of the traffic performance impacts of VSL. The analysis of VSL impacts was performed with VSL OFF and VSL ON.

6.1 MOBILE DATA COLLECTION

The mobile studies were carried out using an instrumented vehicle (Volvo V70) equipped with a computer for automatic recording of trip data. The collected data included travel distance (m), velocity (m/sec), longitudinal acceleration (m/s²), GPS-based information, and continuous video recording of the view ahead of and behind the vehicle (Figure 6.1). The mobile data collection was performed using different drivers. The drivers were recruited by advertisement and included both male and female drivers between the ages of 20- and 60.

The purpose of the studies was to capture detailed driver behaviour data including speed, acceleration and time headway with and without recommended variable speed limits (VSL) under different traffic conditions.

Figure 6.1 Instrumented vehicle during the mobile measurement.
Mobile measurements were undertaken by 40 drivers during a total of 10 days (24\textsuperscript{th}–28\textsuperscript{th} May 2004) before VSL, and over one day (30\textsuperscript{th} September 2004 by 4 drivers) and four days (28\textsuperscript{th}–31\textsuperscript{st} October 2005 by 16 drivers) with VSL. The study covered a 7-km stretch of motorway, see figure 6.2 and investigated driver’s response to the recommended speed displayed on all the gantries that they passed. The data was collection during the morning peak period between 7 and 9.15 am. Each driver made two trips in each direction. The drivers drove freely, choosing a lane on their own without any specific instructions. The purpose of this measurement was to collect information about travel time, speed, acceleration, driver response and speed adoption with regard to a recommended Variable Speeds Limit displayed on the gantries.

![Figure 6.2. The mobile study stretch (blue line) on the southbound carriageway of the E4 motorway.](image)

A large amount of mobile measurement data was collected and analysed. Visualisation of the data such as speed acceleration and brake pressure illustrates where and when speed reductions and deceleration occurred. All events of interest were classified, studied and analysed according to the methods described above.

### 6.2 DATA PROCESSING

All trips were studied and plotted in a speed time diagram, see figure 6.3. Trips were made along a selected 7-km stretch of Södertäljevägen passing 9 gantries from the south to the north of Stockholm and vice versa are shown. For trips toward Stockholm, drivers took 34 minutes and 27 seconds between the start and end points. In the other direction the trip took only 5 minutes and 36 seconds (posted speed limit 90 km/h for both directions). Note the additional travel time caused by congestion for the last three trips. The mobile data collection for the study of driver behaviour focused on the impact of the displayed recommended Variable Speed Limit (VSL) triggered by downstream slow-moving vehicles.
Figure 6.3. Travel time for different trips obtained by the mobile measurements.

Data analyses in this study focused on the deceleration process and adoption of the displayed VSL. To be able to attack the problem from different points of view and compare the resulting behaviour before and after VSL application, three methods were applied. The behaviour of interest is the deceleration process when approaching a slow moving queue and speed adaptation.

1. Study from the moment the driver noticed the end of the queue (checked from video recording in the instrumented vehicle).
2. Study from the moment the driver started braking (automatically registered by the instrumented vehicle).
3. Study from the moment the driver noticed the first displayed VSL until he/she slowed down to approach the end of the queue (checked from video recording in the instrumented vehicle).

These methods differ as the first two consider the deceleration process while the third also considers speed adaptation as the driver approaches the end of the queue. All data collected were classified and analyzed. The data processing included segmentation of the observations as follows:

- based on whether the VSL was OFF or ON
- based on whether the traffic situation was free-flowing or restrained
- based on the initial speed of the vehicles in three groups; under 50 km/h, between 50 km/h and 70 km/h and over 70 km/h.

Plotted speed, acceleration, time, and brake pressure parameters illustrate where and when speed reductions and deceleration occurred, see figure 6.4. This figure includes an interesting...
event when the driver had to reduce speed fast (encircled). All such events were classified, studied and analyzed according to the following methods:

Method 1:

Deceleration process from the moment the driver noticed the end of the queue (controlled from video recording from the instrumented vehicle). The braking process is measured from the point where the queue is observed accompanied by speed reduction until the deceleration process is completed (when the speed reached its lowest level and began to increase again).

Classification

The data were classified in two groups for VSL OFF and VSL ON. The traffic state was thereby considered to be free or restricted. The initial speed the driver drove with is also considered. The speed was classified into three groups: <50 km/h, 50-70 km/h and >70 km/h.

![Vehicle speed acceleration and brake pressure](image)

**Figure 6.4. Example of a mobile trip showing speed, brake pressure and deceleration.**

<table>
<thead>
<tr>
<th>VSL ON</th>
<th>VSL OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free</td>
<td>Restricted</td>
</tr>
<tr>
<td>Initial Speed</td>
<td>Initial Speed</td>
</tr>
<tr>
<td>&lt;50 km/h</td>
<td>&lt;50 km/h</td>
</tr>
<tr>
<td>50-70 km/h</td>
<td>50-70 km/h</td>
</tr>
<tr>
<td>&gt;70 km/h</td>
<td>&gt;70 km/h</td>
</tr>
</tbody>
</table>

*Table 6.1. Structure of classification of different groups.*
Method 2:

Deceleration process from the moment the driver began braking (automatically registered by the instrumented vehicle). Start of braking is chosen at a moment when the driver may not have noticed the end of the queue. The end of deceleration is measured the same way as in the previous method.

Method 3:

Study of braking process from the moment the driver could have observed the first active VSL until he/she slowed down to approach the end of the queue (checked from video recording in the instrumented vehicle). To compare the braking process during VSL OFF and VSL ON all registered decelerations were classified into groups of similar traffic state, (see figure 6.5 for an example of how the relationship and analyses are planned). Different weather conditions were not taken into account.

To investigate speed adaptation, deceleration over the last 400 meters before the end of the queue was studied and analyzed. The road segment was divided into eight 50 meter sections and the average deceleration for each interval was plotted in a graph.
6.3 ANALYSIS

Deceleration process from the moment the driver noticed the end of the queue

Results from the analysis of collected data related to the and braking distance from the moment the driver noticed the end of the queue and deceleration under free and restrained traffic flow conditions with VSL OFF and ON are shown in figure 6.6.

![Graph showing average deceleration and brake distance under free and restrained traffic flow conditions during VSL OFF and ON.](image)

**Figure 6.6. Comparison of average deceleration and braking distance under free and restrained flow conditions during VSL OFF and ON.**

The results from statistical analyses showed that there was no significant difference in average speed changes for periods of VSL OFF and ON. For free flow conditions significant differences were observed in the form of short braking distances and heavy average deceleration during periods when VSL was ON, see table 6.2.
### Table 6.2. Statistical results of traffic under restrained and free traffic conditions during VSL OFF and ON.

For both, free and restrained traffic conditions the braking distance during VSL OFF periods was between 100- and 400m before passing the gantry, while during periods with VSL ON the braking distance varied between 50 and 250 m.

#### Deceleration process from the moment of braking

The same data were used to study the deceleration process from the moment the driver started braking (automatically registered by the instrumented vehicle). The analysis performed in this study showed almost identical results to the analysis above for the deceleration process from the moment the driver first noticed the end of the queue.

#### Speed adaptation and deceleration process from the moment the driver noticed the first displayed VMS.

In this study the whole trip was analyzed and all encircled events similar to the example shown in figure 6.4 were studied to capture the process from the time the driver noticed the first active VMS until he/she slowed down to approach the end of the queue (controlled from video recording from instrumented vehicle). These events were later plotted in speed diagrams where the driver behavior could be easily monitored. Figure 6.7 illustrates the driver’s chosen speed in relation to the posted speed during free and restrained traffic flow conditions. It also shows the point where the driver first noticed the queue and the deceleration actions during periods of VSL OFF.
Figure 6.7. Speed and deceleration process under restrained and free traffic conditions during VSL OFF for vehicles approaching a queue.

It was found from all plotted graphs that registered brake pressure occurred close to the position when drivers observed and then approached the queue, see examples in figure 6.7.

The deceleration process was further studied for free and restrained traffic flow conditions during periods with VSL ON, see figure 6.8. This figure shows a typical free flow deceleration pattern from the point where the driver first observed the recommended speed limits, until the completion of the deceleration when reaching the end of the queue. The drivers travelled at speeds higher/lower than the posted limit speed according to traffic conditions ignoring the displayed recommended speeds. Similar behaviour was noticed in the
plotted graphs where the registered brake pressure occurs close to the position when drivers observe and then approach the queue, see examples in figure 6.8.

![Registered driver's speed and deceleration during free traffic flow condition with VSL ON](image)

*Figure 6.8. Illustration of typical deceleration processes under restrained and free traffic flow conditions during VSL ON for vehicle approaching a queue.*

Statistical analyses were performed to study deceleration behaviour for driving in **restrained** traffic conditions during periods of VSL OFF and ON. The results of the analyses showed no significant difference in average deceleration between the two traffic flow conditions. Higher deceleration appeared in the last 50 meters before the end of the queue, see figure 6.9.
A statistical analysis was again performed to study deceleration behaviour under free-flowing traffic conditions during VSL OFF and VSL ON periods. Again the results showed no significant difference in average deceleration between the two cases. Higher deceleration appeared again in the last 50 m before the end of the queue, see figure 6.10. The variance was significantly higher under free traffic flow conditions during VSL ON.

**Figure 6.9. Comparison of deceleration behaviour under restrained traffic conditions during VSL OFF and VSL ON for vehicles approaching queue.**

**Figure 6.10. Comparison of deceleration behaviour under free traffic conditions during VSL OFF and ON for vehicle approaching queue.**
The conclusions from this study are as follows:

- There was no significant difference in average deceleration under restrained traffic condition with VSL OFF or VSL ON.
- There was no significant difference in average deceleration during free following traffic condition with VSL OFF or VSL ON.
- Under both free and restrained traffic conditions the brake distance during VSL OFF periods was between 100-and 400 m before passing the gantry, while during periods with VSL ON the braking distance varied between 50 and 250m.
- The registered brake pressure occurs close to the position where drivers observed and then approached the end of the queue

Discussion

In-depth studies of driver behaviour and response to variable recommended speed signs are needed in order to assess the impacts of VSL on traffic performance. In the present study it was observed that drivers did not adapt their speeds to the displayed VSL, while at the same time the VSL seemed to make drivers more cautious with regard to the possibility that there would be a queue ahead. Drivers who had been warned by active VSL had a significantly higher but more even deceleration, which increased closer to the queue. Drivers approaching a queue without pre-warning from displayed VSL speed limits both accelerated and decelerated before they arrived at the end of the queue. The deceleration during free flow conditions was almost twice the deceleration during restrained traffic flow. Furthermore, the braking distance was longer during VSL OFF with a range between 50- and 450 m as compared to 50-250 m for VSL ON.

To draw a conclusion regarding the impact of the VSL on travel time along the E4 comprehensive mobile measurements on longer stretch of road are needed. Another approach is to calculate travel time based on MCS detector data.
CHAPTER 7 SIMULATION BASED EVALUATION

In the previous chapters the impact of VSL was empirically studied based on comparisons of traffic performance during periods before and after implementation of VSL. However, due to the random nature of the occurrence of incidents it was difficult to identify time periods with comparable traffic conditions. An alternative method to evaluate VSL is to conduct controlled experiments using a simulation model which has been calibrated and validated for the actual site conditions.

Traffic simulation models are suitable tools for studying advanced dynamic traffic management systems at the operational level. Simulation models have the ability to capture the dynamic behaviour of the individual divers as they react to the perceived traffic situation and managements. Microscopic traffic simulation models allow a detailed representation to be made of the traffic control system under study capturing the behaviour of drivers in response to developing traffic conditions. However microscopic traffic simulation models need to be calibrated and validated for the studied system and traffic conditions before they being used to evaluate ITS. The steps presented in figure 7.1 will be used in this study accomplish this and thereby create a platform for test different strategies to evaluate the VSL impacts on traffic performance.

![Diagram](image)

*Figure 7.1. Applied methodology framework for the simulation study.*
In this study the micro-simulation model VISSIM (VISSIM, 2009) was used. VISSIM is a discrete, stochastic, time step based (1 sec) microscopic model with driver-vehicle-units as single entities. The model contains a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements. The model is based on the work of Wiedemann (1974 and 1991. The VISSIM modelling environment supports programming of external MCS and other ITS-logic and functionality with a high degree of detail. This includes simulation of road-user responses and behaviour to the displayed VSL and usage for evaluation and development of more effective control system.

Simulation models require a detailed and complete description of the layout of the site in order to produce a realistic output. The important features that are usually represented include the location of on-ramps and off-ramps, the number of lanes and location of lane drops, motorway curvature, auxiliary lanes, and weaving sections and the arrangement of loop-detectors on the mainline.

Like many other simulation models, VISSIM requires information defining two types of data classified as supply and demand. The supply side includes the physical road network geometry, implementation and location of the surveillance hardware system including the Variable Speed Limits (VSL) and the embedded algorithm, while the demand side includes dynamic data including flows, vehicle type and composition, route choice, traffic characteristics and driver behaviours.

In this chapter a procedure for constructing and calibrating a detailed model of the E4 segment using VISSIM is presented. This test site presented several challenges for microscopic modelling: an MCS with several gantries 300-500 m apart, several on and off-ramps and several interacting bottlenecks. Field data used as input to the model were compiled from two separate sources: field data and data recorded by MCS microwave detectors on the motorway mainline lanes. The model development procedure consists of: 1) identification of important geometric features, 2) collection and processing of traffic data, 3) analysis of the mainline data to identify recurring bottlenecks, 4) VISSIM coding, and 5) calibration based on observations from 2). A qualitative set of goals was established for the calibration. These were set with relatively few modifications to VISSIM’s default driver behaviour parameters. Different scenarios were tested, including a scenario applied in this study to test the impact of the recommended VSL with various assumptions regarding VSL compliance.

The base case represented existing conditions and will be compared to the performance of the network under different percentages of drivers complying with the speed recommendations.

The process and steps involved in representing the physical network, including the chosen segment of the motorway, vehicle types and composition and other important objects needed are outlined below.

### 7.1 NETWORK PREPARATION

#### 7.1.1 Geometric data

A 7 km stretch of Södertäljevägen, the southbound carriageway of the E4 motorway, was chosen to be modelled in VISSIM. A detailed lay out of the motorway’s road geometry based on links and connectors representing the physical motorway were constructed. The model is based on aerial photographs in bitmap format downloaded from the National Land Survey’s
website (www.lantmateriet.se) used as a background. Scale was established on this image by matching landmarks with the maps obtained from the Swedish National Road Administration (SNRA). Links and link connectors were then traced on this background image in VISSIM. The road geometry maps (consisting of lanes, lane type, width, length, designed speed, on- and off-ramps segments) posted speed and maps of Motorway Control Systems, gantries, detectors and location maps were obtained from the SNRA.

The segment consists of 3 3.5-meter-wide lanes with 4 on-ramps and 2 off-ramps. All on-ramps and off-ramps are uncontrolled. After 3.5 km the motorway splits into two parts. One part continues as a 2-lane motorway and the other leads traffic towards the tunnel Södra Länken in two other lanes. The speed limits on the studied segment varied from 70- to 90 km/h, see figure 7.2. This model involves only motorway through-lanes and ramps and not the adjacent arterial network. All on and off-ramps within the studied stretch were modelled according to the recommended method described in the VISSIM manual (PTV, 2009). The vehicles entering from the on-ramp join the mainline stream by changing lanes within a merge section.

![Figure 7.2. Illustration of the coded E4 motorway.](image)

The modelled study area was been extended to 1.5 km from the beginning of the stretch and 1.5 km at the end of the studied stretch to allow sufficient time and distance for the model to better develop the traffic stream characteristics reflected in the real world (Dowling, R. et al., 2004).

### 7.1.2 Links and connectors

To model the links (including the number of lanes and the width of each lane) and connectors, a series of parameters needed to be identified, including link type (behaviour model) and connectors’-parameters (lane change distance). The modelled motorway is illustrated in figure 7.3, where the blue lines represent links and the pink lines connectors.
7.1.3 Motorway Control System (MCS)

In addition to the motorway geometry, coding of the supply side of the model also entailed the placement of the surveillance system and the controlled hardware elements, MCS loop detectors and VSL signals for each lane at strategic locations in conjunction with Variable Speed Limits similar to the real locations.

MCS detectors are located in groups with one detector for each lane and direction. The aim of the placement of these detectors is to capture the total traffic volume in a particular lane or location. The location of these north-and southbound detectors are shown in figure 7.2.

7.1.4 Data collection points

The data collection points were located in the appropriate place similar MCS detectors. In VISSIM these data collection points have the capability to record a wide range of information simultaneously. For the purposes of this study, data was collected at five minute intervals in order to more accurately record the variation in the data over the modelled period. The data are collected with regard to flows and speeds at the point in the network where survey data was available.

7.2 DEMAND PRESENTATION

For this study data was originally collected for the two previously mentioned empirical studies. The collected data consist of stationary data from video filming and mobile data.
during periods before and after implementation of the Motorway Control System (MCS). In addition, data from MCS detectors were collected for two weeks, including the first week of November and December 2004. The input data required by the microsimulation model are described below.

7.2.1 Vehicles characteristics and traffic composition

VISSIM provides an interface to model different vehicle types and classes. Many parameters of a vehicle type are defined using distributions so that the stochastic nature of a traffic situation can be reflected realistically. The distribution defines the variety of vehicle dimensions within a vehicle type. This will have an effect on simulation results due to vehicle length and width. VISSIM uses a hierarchical concept for vehicle data. The first level is vehicle type including a group of vehicles with similar technical characteristics and physical driving behaviour. One or more vehicle types are combined on the next level, namely vehicle class. In vehicle class, speed distributions, evaluations, route choice behaviour and other network elements are applied. For the purpose of this study, 5 different individual vehicle types were defined as follows: Car, Heavy Vehicle (HGV), LGV (with trailer and articulated) Bus, and Motorcycle (Mcy). Four vehicle classes were created from the vehicle types mentioned above. These classes are defined as Car, HGV, Buss and Mcy.

Traffic composition describes the mix of different vehicle types and the total volume in vehicles per hour. Traffic composition data were especially obtained for the calibration of VISSIM. These data were obtained from field studies, see table 7.1.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Main line</th>
<th>On-ramp</th>
<th>Off-ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>0.934</td>
<td>0.944</td>
<td>0.952</td>
</tr>
<tr>
<td>Bus</td>
<td>0.003</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>LGV</td>
<td>0.041</td>
<td>0.052</td>
<td>0.035</td>
</tr>
<tr>
<td>HGV</td>
<td>0.015</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Mcy</td>
<td>0.006</td>
<td>0.007</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 7.1. Vehicle composition classification and percentage for each lane and on-and off-ramps.

7.2.2 Traffic flow data

Traffic demand, is represented by the flow entries. The interval and the turning fraction of vehicles at the decision points and the data used to generate the demand information include:

- MCS detector data: The traffic Control Centre database gather data from the whole segment of the E4 motorway implemented with the MCS-system, a distance of almost 20 km. The data included traffic flow and average speed per minute per lane per gantry, mainline flow data and the on- and off-ramps flow data.

- Stationary measurements on the motorway main line for two days before and after activation of the VSL from 6 am. to 6 pm. including detailed information about traffic flow and composition, speed, and time headway per vehicle per lane, (see chapter 5). Furthermore, two days of video were processed to calculate the traffic flow converging at one on-ramp and diverging at one off-ramp.
7.2.3 Routing Decisions

In VISSIM traffic demand is supported by two different methods:

- Static routes using routing or direction decisions
- Dynamic Assignment of routes using O-D matrices

According to the first method traffic follows a sequence of links when diverging at exits using turning percentage. Parameters necessary to change lane dictate how far in advance each vehicle will be able to anticipate the next exit.

The second one is Dynamic Assignment of routes using O-D matrices, which contain the average number of vehicles going from every entry origin to every destination.

The first method was used in this study; this requires the location of decision points on the motorway. Each destination point is assigned a proportion of the total flow passing over the decision point. In this way the traffic flow will be distributed to the mainline and the off-ramps see figure 7.3. The red bars indicate the decision points and the green bars the destination points.

These routes include positions, which demand necessary lane changes, for example when approaching on-or off-ramps. The lane changing process including the distance needed for the vehicle to change lane before approaching the off-ramp and the aggressiveness of lane changing are defined. Special attention was therefore paid to locating these points properly to avoid unrealistic queue building due to vehicles attempting to leave by the off-ramp and changing lane at the last minute, see figure 7.4.

![Figure 7.4. Static routes using turning percentage](image-url)
7.3 CALIBRATION
The objective of calibration is to re-construct typical real-world traffic variation in simulation. In the traditional process of model calibration, model parameters are adjusted until reasonable (qualitative and quantitative) correspondence between the model and field observed data is achieved. Model validation covers the process of checking to what extent the model replicates reality.

Model calibration entails checking that the model is performing logically and that all the elements of the network are accurately represented. During the empirical study many different types of data of sufficiently high level of detail were collected simultaneously along the motorway. These data will partly be used to calibrate the VISSIM model. Some data not used in the calibration will be used as benchmarks to which simulation model output will be compared in order to validate the model. Calibration will include indication of key parameters used to model driver behaviour. Fine-tuning sensitive parameters is a part of site-specific calibration to seek agreement with the measured data.

Running the simulation model and reviewing the animation is useful to identify coding error. Animation output facilitates the evaluation of vehicle behaviour and the assessment of its overall plausibility. Attention was paid to monitoring speed, lane change and weaving behaviour at motorway on-and off-ramps to improve the routing decision locations.

The general model calibration procedure is iterative, see figure 7.5. Its purposes are to minimise differences between traffic flow and average speed along the motorway and speeds extracted in the field:

- Initial estimates of the model parameters, through available information concerning the geometric and functional characteristics of the facility

- Vehicular flow simulation and extraction of the flow and speed at each gantry along the studied segment.

- Comparison between simulated and experimental speed and flow.

- If the differences appear meaningful, a modification of parameters is necessary

- If the differences are not relevant, the procedure ends after a comparison of simulated and experimental vehicular flows at each gantry. Excessive discrepancy between the gantry flows may indicate that a new parameter calibration is needed.
With model input (network supply and traffic demand) fixed as described in the previous section, an initial simulation experiment was run using default driver behaviour parameters. No adjustment of VISSIM parameters was made; the calibration was performed by assuming the default normal driver behaviour to be represented by aggressiveness and awareness factors in VISSIM. During this process a need for additional priority rules was identified.

The next step is calibration of the model. The calibration involves checking the model results against observed data and adjusting parameters until the model results fall within an acceptable range of error. The collected data included motorway traffic volume and speed for low traffic periods. The immediate observation here is that there is a severe blockage end of the motorway that produces a queue which quickly overruns the entire site. This problem was caused by a large number of vehicles attempting to exit by the last two off-ramps but were unable to complete the necessary lane change, and stopping at the emergency stop position. Several adjustments to the routing-imposed lane change parameters and look-back distance were made to correct this problem.

The number of time steps per simulation second that a vehicle's position is updated in the model was set at the maximum simulation resolution of 0.01 seconds. The data from each simulation run e.g. traffic flow data and speed were recorded five minutes intervals for 15 gantries. These data were plotted and compared with the data from the MCS detectors (field data).
7.3.1 Desired speed distributions

On the chosen motorway segment there are two posted speeds 90 km/h and 70 km/h see figure 7.1. From field observations it is noticed, as it was usually known that some vehicles did not follow the exact posted speed, that some driver travel at a desired speed, which exceeds the posted speed, whilst others drive more slowly than the posted speed.

To capture these variations the speed distribution was derived from the observed data from 16 gantries over 10 days. Data on traffic flow and speed were plotted for a period of time between 6 am and 6 pm. These figures show that low traffic flow occurs during periods between 11 am and 1 pm. Research by VTI, (Carlsson, A.Cedersund, H. Å., 2000), designed to represent stretches of the same mainline with a posted speed of 90 km/h and 70 km/h respectively confirms this conclusion. To replicate the reality, the above-mentioned posted speeds have been placed in the VISSIM model at the same location as those on the motorway. In this way the vehicles passing the posted speed will receive a new desired speed distribution to adjust their speed according to that posted speed.

Considering low traffic flow, the stochastic distribution of desired speeds (free flow speeds) were defined for the two roadway segments with 70 km/h and 90 km/h, see figure 7.6.

The VISSIM manual recommended that it is advantageous to use reduced speed areas in short sections of slow speed e.g. curves or bends instead of using desired speed decisions. When vehicles arrive at a reduced speed area they are assigned a new desired speed from the corresponding speed distribution. After leaving the reduced speed area, the vehicles get their previous desired speed.

The reduced speed area was applied to the off-ramp sections in the model where the vehicles are assigned a new lower speed to match the field speed characteristics.
7.3.2 Driver behaviour

Drivers’ behaviour and their interaction with other drivers including desired speed, acceleration, time headway and lane changing vary stochastically and affect the way they travel through the road network.

Driver behaviour parameters are grouped into links or connectors. The parameters related to connectors including weaving behaviour and necessary lane changes are as follows:

- Look back distance, which is the distance upstream of the ramp within which the vehicle begins to attempt to manoeuvre or change lanes. In reality this distance is correlated to the information provided to the driver about the oncoming bifurcation. The default value is 200 m.

- Emergency stop distance: Distance before the bifurcation where the driver will stop if he/she has not reached its desired lane. The default value is 5 m.

- Waiting time before diffusion.

VISSIM offers different models of link based behaviour. These include among others, two versions of the Wiedemann car following model: freeway driver and urban driver. For this model the car following model chosen is based on Wiedemann 99, which is suitable for interurban (motorway) traffic. In VISSIM, driver behaviour is linked to each link by its link type. The car-following model can be modified through 10 tuneable parameters. The most important parameters are CC0 (standstill distance, desired distance between stopped cars), CC1 (headway time, in seconds).

The safety distance $dx_{\text{safe}}$ at a given speed (m/sec) is thus computed to:

$$dx_{\text{safe}} = CC0 + CC1 \times v$$

CC4 and CC5 (following threshold) control the speed differences during “following state”. These parameters have most impact on the road capacity (Hagyi, A. 2008)

7.3.3 Adjustments to the lane change distance

Lane change defines the distance at which vehicles will begin to attempt to change lanes (e.g. distance of signpost prior to a junction, VISSIM, 2009). It was determined that the default lane change distance of 200 m was too small for large numbers of vehicles crossing over several lanes of traffic to reach their exit. The value was increased to 500m. Higher values were used but this resulted in the unrealistic effect of bunching up all the exiting vehicles in the right most lanes, far upstream of their intended off-ramp. These vehicles obstructed other upstream on or off-ramps. It was necessary to tune the lane change distance individually for each off-ramp, in a way that allowed vehicles sufficient weaving space while ensuring that these lane-change regions did not overlap. Higher values were needed in two places where the road diverges in a way that is not similar to the off-ramps, i.e. where the road diverges to the Södra Länken tunnel.
7.4 VALIDATION

The model was validated using data from a different day. In visual validation, graphical representations of the outputs from the observed and simulated systems were used. Validation of flows and speeds for off-peak periods is presented in figure 7.7.

![Figure 7.7. Validation results, observed vs. simulated flows during off-peak periods.](image)

Statistical validation of the simulation model was based on goodness-of-fit measures related to speeds and flows. Common measures are the root mean square normalized error (RMSNE).

\[
\text{RMSNE} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left( \frac{y_{n}^{\text{sim}} - y_{n}^{\text{obs}}}{y_{n}^{\text{obs}}} \right)^{2}}
\]

where \( y_{n}^{\text{obs}} \) and \( y_{n}^{\text{sim}} \) are the average of observed and simulated measurements at space-time point \( n \) respectively, calculated from all available data. Table 7.2 summarizes the results for the off-peak periods. The results indicate reasonable overall fit, and good ability to replicate the spatial and temporal variability in data.

<table>
<thead>
<tr>
<th>Gantry no.</th>
<th>47465</th>
<th>48290</th>
<th>48935</th>
<th>49770</th>
<th>50570</th>
<th>51085</th>
<th>51630</th>
<th>52220</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSNE</td>
<td>0.09</td>
<td>0.10</td>
<td>0.08</td>
<td>0.10</td>
<td>0.11</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 7.2. Goodness-of-fit statistics for flows during low traffic period for the selected gantries.

The traffic demand on the motorway during peak hours exceeds capacity almost every day. This results in traffic jams and shock waves due to disturbance in the traffic flow. These shock waves propagate several kilometres upstream and exist for a long time. Running the simulation with the peak traffic demand showed that the motorway had sufficient capacity. To replicate the downstream bottleneck a ‘virtual’ shockwave was introduced by adjusting the exit capacity at the end of the stretch.
This was validated and the validation of flows for peak periods is shown in figure 7.8.

![Image](image1)

**Figure 7.8. Validation results, observed vs. simulated flows during peak period.**

Statistical validation of the peak period was performed as summarized in Table 7.3. The results indicate reasonable overall fit and good ability to replicate the spatial and temporal variability in data.

<table>
<thead>
<tr>
<th>Gantry no.</th>
<th>47800</th>
<th>48935</th>
<th>49770</th>
<th>50395</th>
<th>56890</th>
<th>51085</th>
<th>51630</th>
<th>52220</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSNE</td>
<td>0.12</td>
<td>0.14</td>
<td>0.18</td>
<td>0.20</td>
<td>0.16</td>
<td>0.18</td>
<td>0.18</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Table 7.2. Goodness-of-fit for flows during peak traffic period for the selected gantries.**

Validation results of speeds exhibit simulation in two gantries along the motorway.

![Image](image2)

**Figure 7.9. Validation results, observed vs. simulated speeds during peak period.**

After calibration and validation of the peak periods the Automatic Incident Detection (AID) algorithm was implemented in the simulation model as described below.
7.5 REPLICATIONS

Results obtained from the microsimulation model represent different outputs in every run. It is therefore insufficient to only examine the results of a single run. To determine the number of simulation runs, the mean and standard deviation of a number of performance measures from a number of simulation runs was used. This was calculated according to the mean and standard deviation of speed and traffic flow as follows (Toledo and Koutsopoulos 2004; Chu et al. 2004):

\[ N = \left( \frac{t_{\alpha/2} \cdot \sigma}{\mu \cdot \varepsilon} \right)^2 \]

where \( \mu \) and \( \sigma \) are the mean and standard deviation of the performance measures. 95% confidence interval and a 10% allowable error (\( \varepsilon \)) were used in the calculation and \( t_{\alpha/2} \) is the critical value of studen’s t-test at confidence level \( \alpha \). For this case 10 runs were conducted to achieve statistically significant performance measures.

7.6 IMPLEMENTATION OF THE AID ALGORITHM

To simulate the operations in VISSIM, the Automatic Incident Detection, AID, (see section 3.3.4 for a detailed description of the ALD algorithm) was implemented in VISSIM using VisVAP.

The AID speed features of 9 groups see figure 7.10, (3 cross sections/gantries of 3 lanes) are collected in a shifting process. Gantry 1, 2, 3 and then gantry 2, 3 4 and gantry 3, 4, 5 and so forth for all 15 gantries on the studied segment of the E4, see figure 7.1.

*Figure 7.10. Sketch of the E4 motorway including four cross-sections/gantries of three lanes.*
The average speed on the three lanes in three sections was compared with speed thresholds. The comparison will be as follows:

For the section with posted speed 90 km/h if the detected speed is:

- < 35 km/h the VSL will be ON
- > 50 km/h the VSL will be OFF

For the section with posted speed 70 km/h, if the detected speed is:

- < 22 km/h the VSL will be ON
- > 35 km/h the VSL will be OFF

When the obtained average speed exceeds the thresholds for gantries 1, 2 and 3 a lower recommended speed will be displayed 30 km/h on gantries 1 and 2, 50 km/h on gantries 3, and 4, 70 km/h in gantries 5 and 6, and so on. The flow chart of the AID algorithm implemented in VISSIM is illustrated in figure 7.11.
Figure 7.11. The Automatic Incident Detection (AID) implemented in VisVAP.

The flowchart contains subroutine programs (double framed boxes). These subprograms include in turn include other sub-programs (sub-routines), see figure 7.12.
The resulting VISSIM model, enhanced with the above capabilities, represents an integrated test-platform consisting of a well calibrated and validated simulation model with logic modules corresponding to existing and other ITS-functions (VSL, ramp-metering, etc) to be tested.

7.7 RESULTS: IMPACT OF COMPLIANCE

The validation of the VISSIM simulation model described above proved is capable of reproducing the actual traffic conditions in the road network, with an acceptable degree of accuracy. The validated model was used for the simulation experiments to evaluate a range of operational strategies related to VSL.

In section 5.5.5, drivers’ compliance was investigated. The results showed that drivers, to a large extent, ignored the displayed recommended speed. In this section, the calibrated and validated VISSIM model of the E4 motorway was used to evaluate the effectiveness of VSL, and how sensitive the results are to driver compliance is. The following scenarios were examined: base case (no VSL) and VSL with 25%, 50%, 75% and 100% driver compliance. Under the VSL scenarios compliant drivers follow the VSL recommendations, while non-compliant drivers move according to prevailing traffic conditions and their original desired speeds. The compliant drivers adapt their speed to a new speed distribution considering the displayed recommended speed as they pass a 200-300 m section before the gantries where matrixes displayed recommended low speeds. The results that follow are based on ten replications. Average speed and traffic flow for each gantry at 5 minutes intervals were used to evaluate the performance of the system under each scenario. Furthermore, travel times were also compared across scenarios.
Effectiveness of VSL

The two graphs in figure 7.13 summarize the spatial and temporal speed distribution in the base case (top) and the VSL case with 100% compliance (bottom). The x-axis represents time of day and the y-axis gantries location along the motorway. The corresponding speed variation is indicated by colors, light colors indicating high speeds and red low speeds. The results show that in the base case there are frequent occurrences of short periods with reduced speed as shown in the left portions of the diagram. Under VSL with 100% compliance speeds exhibit less variability and have more uniform distribution across the motorway.

![Speed-Time diagram for the base case](image1)

![Speed-Time diagram for 100% VSL compliance](image2)

Figure 7.13. Speed spatial-temporal distribution for base case (no compliance) and 100s % compliance.

The speed distribution is summarized in Figure 7.14 for different levels of compliance (25%, 50%, and 75%). The effectiveness of VSL is drastically reduced at lower compliance rates. At 25% the system basically has minimum impact during the congested time periods at the chosen locations, with speed distribution almost resembling that with no VSL.
Figure 7.14. Speed spatial-temporal distributions for different compliance scenarios.

Figure 7.15 provides a more detailed view of the impact of the VSL on the evolution of speeds at three gantry locations. At these locations, the introduction of VSL resulted in delayed onset of congestion and associated speed breakdowns and higher overall speeds.
Figure 7.15. Evolution of speeds for base case (no compliance) and 100% compliance.

The impact of the VSL is reflected by maintenance of the desired level of speed for a longer time during the studied time period, see figure 7.15.
The impact of driver compliance was evaluated using travel times as measure of performance. Figure 7.16 shows the average travel times from the beginning to the end of the studied motorway segment for each scenario by time of day. Travel times are clearly lower under the VSL scenario with 100% compliance. However, as the level of compliance decreases, travel times increase.

![Travel time during congestion conditions](image)

*Figure 7.16. Travel times for various scenarios.*

**Discussion**

A Motorway Control System (MCS) with mandatory or advisory Variable Speed Limits (VSL) can be used to improve traffic performance on motorways under congested conditions. This study applied micro-simulation with the embedded AID algorithm to examine the effectiveness of VSL for using the MCS on the E4 motorway in Stockholm with advisory speed signalling as a case study. In particular, the study has presented results concerning the impact of driver compliance on the effectiveness of advisory VSL. These results indicate that the VSL contributed to delayed onset of congestion and associated speed breakdowns, higher overall speeds. However, the effectiveness of VSL deteriorates as rates of compliance decrease.
7.8 EVALUATION OF VSL WITHOUT DOWNSTREAM CAPACITY CONSTRAINTS

In the previous chapter we used the data to examine the impact of VSL on E4. The results indicate that the impact is not very clear. We also examined, using simulation, the effect of driver compliance on the effectiveness of VSL. These results indicate that the system can be more effective if it operates as mandatory.

However, the overall conditions on this section of the E4 are very congested with potential events downstream (and outside the boundaries of the network) that impact the observed conditions. Therefore, and in order to draw conclusions about the VSL system and its logic, we conducted a series of simulation experiments with the same network but after removing downstream capacity constraints. The objectives of the VSL in this study are:

A. VSL under incident conditions. The base network is used with the current demand (but without capacity constrains at the exit boundary).

B. VSL under recurrent conditions. The base network is used with the demand increased by 10%. This demand is enough to generate congestion (but not at the level observed in the field).

7.8.1 Incident scenario

Non recurrent events are unplanned physical events caused by accidents, collisions, spilled loads, vehicle breakdowns on the hard shoulder or other random events. Incidents may cause reduction of road capacity and creation and propagation of queues. Incident handling requires development of strategies and systems for dynamic traffic management as means to improve the operations of the traffic network. This section deals with the use of the VISSIM E4 model to assess the potential impacts of the motorway management system VSL on accident-related congestion on the E4. The simulation model includes the implemented AID algorithm, which activates the VSL to display lower speed limits to drivers upstream to warn them of a queue downstream. The AID system has no ability to confirm that an incident has actually occurred, but it can detect low speeds of vehicles approaching or passing the area where the incident occurred. The activation of the VSL may achieve improved overall performance that reduces the delay on the motorway during incident.

The occurrence of traffic incidents along a motorway is closely related to disturbances, speed, and travel time variability. The incident tested in this case is a simple one lane blockage on the downstream section of the study E4 motorway. It occurred 2,500 seconds after the start of the simulation and lasts for almost an hour. Figure 7.17 shows the configuration of the congested motorway section with the incident.
Two operational scenarios were tested. Both scenarios were identical except for the application of the VSL in the second scenario, the displayed recommended speed was assumed to be compulsory with all drivers following the displayed speed (100% compliance). In order to identify the impact of the incident with and without the VSL implementation, simulations were performed for both scenarios. To capture the spatial and temporal impacts of the MOEs of speed, traffic flow and travel time were collected for both cases. These data were extracted for 15 gantries over 3 hours at 5-minutes intervals.

A comparison of speeds for the two scenarios with and without VSL (100% compliance) for each gantry shows obvious differences (see figure 7.18). The figure illustrates that the VSL reduces disturbances and increases the speed after the incident more efficiently than the case without the VSL.
Furthermore the results of the investigation indicate that VSL has a positive impact on travel time, see figure 7.19, with reduction of 9% after application of the VSL.

Figure 7.18. Speed diagram for all gantries for the 0% and 100% compliance scenarios.

Figure 7.19 Travel time during accident with and without application of the VSL (100% compliance)
In summary, the application of VSL forcing drivers upstream to follow the displayed lower speed could reduce the congestion impacts of an accident.

### 7.8.2 Recurrent congestion scenario

As mentioned previously, in two scenarios the network (with the modified exit capacity) has sufficient capacity. Demand was therefore increased by 10% to create moderate congestion and study the VSL performance.

The same segment of the E4 motorway modelled in the microscopic model VISSIM was used (Figure 7.2). This model included the implementation of the Automatic Incident detection (AID) algorithm, see section 7.5. The motorway has four on-ramps and two off-ramps. The displayed recommended speed was assumed to be compulsory with all drivers following the displayed speed (100% compliance).

The motorway speed map with VSL OFF (Figure 7.20 top) provides insight on the positive impacts of VSL (Figure 7.20 bottom). VSL contributed to reduction of high momentary speed fluctuations.

![Speed-Time diagram for 10% higher demand without VSL](image1)

![Speed-Time diagram for 10% higher demand with VSL](image2)

*Figure 7.20. Speed diagrams for all gantries for increased demand scenarios with VSL OFF and VSL ON and 100% compliance.*
Travel time for trips along the mainline were also obtained, see figure 7.21. Positive results such as homogenization were observed with significant travel time reduction.

![Travel time along the main line](image)

*Figure 7.21. Travel time for the mainline with and without VSL with demand increased by 10%.*

**Discussion**

This study applied micro-simulation with the integrated AID algorithm to examine the effectiveness of VSL. The implemented VSL was assumed to be compulsory. Two scenarios were designed and tested to (incident and recurrent congestion).

The potential impacts of VSL on accident related congestion on E4 was studied. A comparison of speeds at each gantry for VSL OFF and VSL ON with 100% compliance indicates that the VSL reduces disturbances and increases the speed after the incident more efficiently than the case without the VSL. Furthermore, the results of the investigation also indicate that VSL has a positive impact on travel time. Under recurrent congestion VSL also had positive impact leading to reduced speed and speed fluctuations.
Ramp metering refers to traffic control strategies used to regulate the number of vehicles entering the motorway (Papageorgiou, M. et al., 2008) with the aim of reducing. In this section, two types of intelligent transportation system (ITS) were tested to determine their effectiveness in terms of travel time and efficiency. These two ITS strategies include variable speed limits (VSL) and ramp metering. The effect of using VSL separately, ramp metering separately and combination of the two were simulated along the same section of the E4 motorway. The ALINEA ramp metering control strategy, proposed by Papageorgiou, M. et al. (1991), was used.

The ramp metering control strategy ALINEA was implemented on four on-ramps. The ALINEA strategy applied in this study is a local control algorithm. Vehicles are controlled by a traffic light according to a metering rate based on real-time occupancies in the mainline downstream of the onramp. Queue override to avoid excessive queues and queue spill back and the minimum/ maximum allowed rates were considered.

### 8.1 IMPLEMENTATION OF THE ALINEA ALGORITHM

ALINEA (Asservissement Linéaire d’Entrée Autoroutière) is a simple local reactive ramp metering strategy based on a feedback principle proposed by Papageorgiou et. al. (1991). Real-time traffic measurement in the vicinity will be collected to calculate suitable metering rates with the aim of maintaining an optimal occupancy on the mainline such that the combined flow from the main stream and on-ramp will not exceed system capacity.

Ramp metering rate is determined based on local conditions such as real time flow and occupancy data. ALINEA (figure 8.1), requires one detector station in the desired location on the mainline immediately downstream of the entrance ramp to measure the occupancy $O_{\text{out}}$, the constant $K_r$, and the update cycle of each metering rate. The advantage of ALINEA is its ability to react even to slight differences between $O_{\text{out}}(k)$ and $O_{c}$ and thus may prevent congestion by stabilizing the traffic flow at a high throughput level (Papageorgiou, M. et. al. 2003). Regardless of the upstream traffic flow, the feedback law in ALINEA attempts to attain desired occupancy. The closed loop feedback in ALINEA uses the following equation (Papageorgiou 1991) to determine the current ramp metering rate for each on-ramp:

$$r(k) = r(k-1) + K_r [\delta - O_{\text{out}}(k)]$$

![Figure 8.1. ALINEA (Fundamental Diagram. Source: (Papageorgiou and Kotsialos 2002))](image-url)
\[ r(k) = r(k-1) + K_R \left[ \dot{\hat{O}} - O_{out}(k-1) \right] \]

where:

- \( k = 1,2 \) is the discrete time index
- \( r(k) \) is the ramp flow (veh/h) allowed to enter in time period \( k \)
- \( r(k-1) \) is the metering rate in time step \( k-1 \);
- \( O_{out}(k-1) \) is the last measured downstream motorway occupancy (in %) average over all lanes
- \( \dot{\hat{O}} \) is the desired occupancy.
- \( K_R \) is the regulator parameter

The regulator parameter \( K_R \) is used for adjusting the constant disturbances of the feedback control. It was found that in real-life experiments, a value of \( K_R = 70 \) vehicle/hour gave good results. Larger \( K_R \) values tend to reduce the regulation time and lead to stronger reaction.

\( \dot{\hat{O}} \) is a set (desired) value for the occupancy downstream station (\( \dot{\hat{O}} \) may be set equal to or less than critical occupancy \( o_{cr} \), in which downstream motorway flow becomes close to \( q_{cap} \)). The range of values for this parameter varies between 18% and 31% (Chu and Yang, 2003)

The ALINEA algorithm was implemented in VISSIM using VisVAP. During the simulation runs the VisVAP code interprets the control logic commands and creates the signal control commands for the VISSIM network. At the same time, various detector variables reflecting the current traffic situation are retrieved from the simulation and processed in the logic.

The implemented ALINEA logic in VISSIM is summarized in figure 8.2. If current queue on two on-ramps exceeds the maximum size, the maximum metering rate will be applied. Otherwise the ALINEA algorithm will check the occupancies collected by the detector on the mainline downstream of the ramp metering and apply the necessary ramp metering rate.

**Figure 8.2. Methodology Flow Chart**
After the implementation of all the required devices, the ALINEA algorithm parameters should be calibrated (Chu and Yang, 2003). This calibration includes the location of the downstream detector, the optimal occupancy of the downstream detector station $O_c$, the update cycle of each metering rate $k$, and a constant regulator $K_R$. For this application, the methodology used and values of ALINEA parameters recommended in the literature (Papageorgiou, M. et al 1991) and (Chu and Yang 2003) were applied. Papageorgiou (1991, 1997) recommends a regulator $K_R$ equal to 70 due to its good performance in real-world applications. The desired occupancy $O_c$ is set equal to or slightly less than the critical occupancy, or the occupancy value at capacity. The placement of the downstream detector station is presented by gantries downstream of the studied on-ramps. The distances of these gantries from the on-ramps lie within the recommended values, i.e. between 40 m and 500 m. Finally, the value of the update cycle of the metering control is calculated, which may vary between 40 seconds and 5 minutes. For this study the following values were chosen:

- Regulator $K_R$ equal to 70
- Update cycle time 60 seconds
- Occupancies of a range between 18 and 25% were tested

The performance of the ALINEA algorithm depends on the value used as target occupancy. To obtain detailed data of traffic flow, average speed and occupancy, ten replications were applied for the base model. The data were collected at the first gantry downstream of each on-ramp. Flow-occupancy and speed-flow plots for the four on-ramps were obtained. The purpose of this application is to determine the critical occupancy values needed as an important input parameter for ALINEA. The detected data is illustrated in figure 8.3. These data are per lane in 5-minute intervals and include traffic flow and average occupancy.
From figure 8.3, the optimal occupancy is found to be within a range of 15% and 25%. On the basis of these results, the on-ramp metering impact analysis was performed with five levels of optimal occupancy (15%, 18%, 20%, 22% and 25%).
**Effectiveness of ramp metering**

The measure of effectiveness (MOE) used to evaluate the system performance of the ramp metering control algorithm was the OD travel time. This measure of performance considers total vehicle travel time between specific OD pairs. Data regarding total travel time for the whole road network was collected for occupancy scenarios of 20%, 22 and 25%. Ramp metering successfully reduced the network travel time of the congested E4 motorway.

The results showed that almost all ramp metering scenarios reasonably improved the mainline and the other routes travel time. Results showed that 65% of all OD trips had a shorter travel time when 22% occupancy was applied. The ALINEA algorithm with 22% occupancy of was therefore implemented together with the VSL on the E4 motorway to study the impact of two combined ITS control strategies. However, it should be pointed out that the benefits were obtained at some expense of vehicles entering from the on-ramp. The choice of 22% also represents a trade-off with the incoming vehicles.

### 8.2 EFFECTIVENESS OF COMBINED RAMP METERING AND VSL

The potential of combining two intelligent transportation systems (ITS) strategies, ramp metering and variable speed limits (VSL) along the E4 motorway was tested (Figure 8.4).

![Figure 8.4. Combination of VSL and Ramp metering along the E4 motorway](image)

From the application of the combination strategies, VSL and ramp metering the total number of vehicles entering the network over time was detected and plotted, see figure 8.5. More specifically travel times for all vehicles travelling along the mainline and select OD pairs were collected. Application of ramp metering control reduced the inflow from the on-ramp to the mainline, which resulted in reduced travel time for vehicles travelling along the mainline.
Figure 8.5. Total number of vehicles entering the road network during the simulation time period.

Figure 8.6 shows the results of travel time along the mainline, there a combination of the VSL and ramp metering strategies performed well. As the demand increases events occur mainly in the vicinity of on-ramps, leading to low speeds. These low speeds are detected by the AID system, which then activates VSL upstream of the events, forcing traffic to slow down and creating a homogenised flow travelling at more uniform speed. These conclusions concur with Papageorgiou et al. (1997).

Figure 8.6. Travel time for the mainline with and without VSL and ramp metering with 22% occupancy.
Figure 8.7 summarizes the results for the OD pairs defined from the first on-ramp to the end of the section. Ramp metering reduces the impact by 12%. The VSL had a greater impact on traffic flow and travel time than ramp metering. During the combination of the two control strategies the travel time was lower than VSL but this was achieved at expense of reduced from the on-ramp.

![Travel time from first on-ramp to exit](image)

**Figure 8.7. Travel time for the first on-ramp for the base case, ramp metering, VSL and combination of VSL and ramp metering.**

Figure 8.8 illustrate the results for the OD pair from the second ramp to the end of the section. The results are consistent with those obtained for the first on-ramp.

![Travel time from second on-ramp to exit](image)

**Figure 8.8. Travel time for the second on-ramp for the base case, ramp metering, VSL and the combination of VSL and ramp metering.**
Discussion

In this chapter microscopic traffic simulation was used to examine the potential of applying a) VSL strategy under various conditions, b) ramp metering strategy only, and c) a combination of VSL and ramp.

In all cases the strategies were beneficial for the traffic on the mainline. The combined VSL and rampmetering strategy was the most effective with respect to average travel time. However, because of the limitation of the model (that does not represent local streets) other impacts of these strategies were not fully evaluated. So, full estimation of delays for all vehicles entering the system was not assessed.
CHAPTER 9 SUMMARY AND CONCLUSION

9.1 SUMMARY

Over the last thirty years, the development of the Intelligent Transport Systems has led to new ways of managing and operating existing transportation infrastructure. Under ITS, Variable Speed Limits (VSL) have been introduced to improve the operations of freeway facilities under congested conditions. The aim has been to reduce traffic breakdown, increase efficiency, reliability and safety, as well as reduce pollution, without necessitating major physical changes in the road infrastructure. Traffic characteristics such as speed, headway and lane distribution are normally detected and processed by the surveillance systems. This information can then be used as basis for the control as well as for information to the road users regarding traffic conditions.

However, the application of VSL is hampered by the lack of an adequate understanding of the problem’s complexity and its causal mechanism. Various studies have shown that VSL are not necessarily followed by drivers, particularly if the displayed speed is advisory instead of mandatory. The success of dynamic motorway traffic management depends to a large extent on how the drivers respond to the displayed Variable Speed limits (VSL), and their interaction with other vehicles.

In general, the impact and effectiveness of mainline control strategies have mostly been subject to theoretical studies with only limited empirical validation. Empirical studies are not as common. Furthermore, the application of microsimulation modelling of VSL strategies has the potential to test different scenarios under a variety of operating conditions and demand scenarios.

The primary objective of this thesis is to develop in depth knowledge of the traffic impacts of VSL for motorway link control. A theoretical and empirical framework was developed for this task using the assessment of the impact of VSL control strategies on the E4 motorway in Stockholm, Sweden (3 lanes per direction) as a case study. The research applies a bottom-up perspective including empirical driver behaviour studies, full scale field experiments with different strategies, and simulation modelling. Different methods were applied to study the impacts of the VSL on traffic performance.

Comprehensive traffic data (traffic flow distribution, mean speed, mean headway, etc.) were collected during peak periods before and after implementation of VSL in order to analyze the impact of VSL operation on traffic behavior and performance. However, the traffic conditions and the occurrence of incidents vary dynamically, making each traffic situation unique. Thus “before” and “after” conditions were not similar. Therefore, it was difficult to draw definitive conclusions regarding VSL impacts. Recommended speeds are displayed by VSL when low speeds are detected downstream with the intention to warn on-coming drivers, but it cannot be verified to which extent approaching drivers react to these signs or to observing queuing conditions downstream. Therefore, the analysis of VSL impacts based on the empirical data was limited to select time periods exemplifying typical conditions. A method based on the estimation of speed-density relationships before and after was used to overcome these limitations.

The results from this empirical study using the stationary data tend to indicate that the system may not have significant impacts. Previous studies assessed the effectiveness of VSL...
under various conditions and operating strategies. In particular a recent study (Papageorgiou, M. et.al., 2008) of a European implementation of mandatory VSL has shown that VSL has the potential to increase the critical occupancy. Results related to the impact on capacity and critical occupancy, from this study, tend to show some support, but more empirical data and further analysis is required.

A mobile study to assess the impacts of Variable Speed Limits (VSL) on traffic performance was also conducted. It was observed that drivers did not adapt their speeds to the displayed VSL, while at the same time the VSL seemed to make drivers more cautious with regard to the possibility that there would be a queue ahead. Drivers who had been warned by active VSL had a significantly higher but more even deceleration, which increased closer to the queue. Drivers approaching a queue without warning from displayed VS both accelerated and decelerated before they arrived at the end of the queue. The deceleration during free flow conditions was almost twice the deceleration during restrained traffic flow. Furthermore the braking distance was longer during VSL OFF with a range between 50-450m as compared to 50-250 m for the VSL ON.

The Variable Speed Limits (VSL) displayed low recommended speeds as a result of congestion and queues. It was therefore difficult to conclude from the field studies whether the observed traffic performance impacts were primarily caused by VSL signaling or the presence of queues downstream. More extensive data collection covering a wide range of traffic conditions for several days before and after application of the VSL is needed to perform a reliable comparison.

As described above, the impact of VSL was empirically studied without been able to control other variables than the VSL that might impact the traffic conditions. An alternative method to evaluate impacts of VSL, using advanced state-of-the-art, traffic simulation techniques to conduct “controlled experiments” was therefore applied as described below.

Traffic simulation models are suitable tools for studying advanced dynamic traffic management systems at the operational level. Simulation models have the ability to capture the dynamic behaviour of the individual divers as they react to the perceived traffic situations. For this study a systematic experimental design using the microsimulation model VISSIM was used to model a segment of the E4 motorway in Stockholm. The traffic demand on the motorway during peak hours exceeded the capacity leading to recurring congestion in the form of traffic jams and shockwaves due to disturbance in the traffic flow. To operate the Stockholm VSL system in VISSIM, logic similar to the Automatic Incident Detection AID was defined and applied using VisVAP (vehicle actuated programming).

After calibration and validation of the simulation model, the model was used to conduct the simulation experiments needed to evaluate a range of operational strategies to evaluate the MCS.

Initially the impact of VSL was evaluated under current operations conditions on the E4, assuming different levels of driver compliance. The following scenarios were examined: base case (no VSL), VSL with 25%, 50%, 75% and 100% driver compliance. Under the VSL scenarios compliant drivers follow the VSL recommended speeds, while non compliant drivers drove with a speed based on the prevailing traffic conditions and their original desired speeds. Average speed and traffic flow for each gantry in 5 minutes intervals were used to evaluate the performance of the system in each scenario. Furthermore, travel times were also
compared across scenarios. The results indicate that the VSL contributed in the delayed onset of the congestion and associated speed breakdowns, higher overall speeds and higher traffic flow. Moreover, the effectiveness of VSL deteriorated as the rates of compliance decreased. The results show that in the base case there are frequent occurrences of short periods with reduced speed. Under VSL (with 100%) compliance speeds exhibit less variability and have more uniform distribution across the motorway. In particular the speed distribution for different levels of compliance (25%, 50%, and 75%) shows that the effectiveness of VSL is drastically reduced at lower compliance rates. At 25% the system basically has minimum impact. The average travel times from the beginning to the end of the studied motorway were clearly lower under the VSL scenario with 100% compliance. However as the level of compliance decreases, travel times increase.

This study also applied micro-simulation with the embodied AID algorithm to examine the effectiveness of mandatory VSL for hypothetical recurrent and incident congestion scenarios. The study also examined the impact of combined strategies that include VSL and ramp metering. Ramp metering is an effective measure to maintain efficient mainline traffic operations. A number of algorithms have been developed in recent years to ensure effective use of ramp metering for better traffic performance. The same segment of the E4 motorway modeled in VISSIM was used again to test the application of ramp metering. Vehicles trying to gain access to the motorway from on ramps were controlled with a metering rate based on occupancies measured in real time. The local control algorithm ALINEA was chosen and implemented in VISSIM.

Travel times for all vehicles travelling along the mainline were collected. The results show that combined ramp metering and VSL can be very beneficial. However, further analysis is needed to access the impacts more globally. The strategies tend to impact the inflow from the on-ramps and the consequences on the local traffic were not assessed.

In conclusion, the assessment of the impact of VSL is a difficult task because it requires comprehensive datasets from comparable traffic conditions before and after application of the control measure. Traffic simulation models are suitable tools for studying advanced dynamic traffic management systems at the operational level.

### 9.2 CONTRIBUTIONS

Motorway Control Systems (MCS) are generally based on closed feedback loops. This type of management control is complex and dynamic, and depends on the interaction of all components in the system. The communication network for MCS is vital to the operation of the system and must be reliable. Generally, evaluation of this type of systems requires comprehensive data that can capture the variation in traffic conditions. Comparable traffic conditions are needed to compare performance with and without such systems. This thesis evaluated Variable Speed Limits (VSL) systems. The methodology included empirical studies, analysis and controlled experiments using microsimulation. The main contributions of the research include:

- Driver behaviour studies before and after implementation of the VSL focusing on the response of individual drivers to actual traffic conditions and to VSL advisory speed signals. Extensive stationary video data collection (speed, headway, lane changing) and mobile surveys.
- Analysis of the impact of VSL using the fundamental diagram and relationship between speed, flow and density calibrated with empirical data.

- Development of a simulation platform using microscopic traffic simulation including the enhancement, calibration and validation of the model using the collected data on driver behaviour and traffic. The model was then applied for evaluation purposes by means of controlled experiments with different MCS strategies.

  - VSL with different degrees of driver compliance (0 to 100%) to the advisory speed signs.
  - VSL impact at increased traffic demand
  - VSL and ramp metering impacts on travel time, combined or alone.

This work has been presented in different conferences (Nissan, A. et. al., 2006, 2008, 2009).

9.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The research documented in this thesis is a comprehensive attempt to evaluate the impacts of VSL using empirical studies as well as simulation. Further efforts are needed to understand the impact of the interactions between different variables that affect VSL performance as suggested below.

- Comprehensive and detailed driver behaviour studies for better understanding of driver reaction to displayed VSL.

- Detailed evaluation of the Incident Detection Algorithm (AID) logic. This could result in better parameters to be used or improved logic that is more robust with respect to prevailing traffic conditions.

- The results from this study indicate that the system can be more effective if it operates as mandatory. It is recommended to change the status of the displayed variable speed limits from recommended to compulsory to ensure higher driver compliance and a productive impact of the VSL. Detailed driver behaviour studies are needed to confirm this.

- In this study the ramp metering algorithm was implemented with the same occupancy rate of (22%). More detailed studies are needed to select the best occupancy on different on ramp sections in order to obtain better performance.

- Coordinated VSL and ramp metering control strategies need to be developed and evaluated.
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