Cooperative Variable Speed Limit Systems

Modeling and Evaluation using Microscopic Traffic Simulation

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Norrköping 2014
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ISSN 0280–7971

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Printed by LiU Tryck, Linköping, Sweden 2014
Abstract

During the last decades the road traffic has increased tremendously leading to congestion, safety issues and increased environmental impacts. As a result, many countries are continuously trying to find improvements and new solutions to solve these issues. One way of improving the traffic conditions is by the use of so called intelligent transport systems, where information and communication technologies are being used for traffic management and control. One such system commonly used for traffic management purposes are variable speed limit systems. These systems are making use of signs to show speed limits adjusted to the prevailing road or traffic conditions. The rapid development in telecommunication technologies has enabled communication between vehicles, and between vehicles and the infrastructure, so called cooperative systems. This opens up for the possibility to further improve the performance of a standard variable speed limit system by adding cooperative system features.

The overall aim of this thesis is to investigate the potential benefits of incorporating infrastructure to vehicle communication and autonomous control to an existing variable speed limit system. We show how such a cooperative variable speed limit system can be modeled and evaluated by the use of microscopic traffic simulation. Results from the evaluation indicate increased flow harmonization in terms of narrowing of the acceleration rate distribution and reduced exhaust emissions.

Further, we compare four control algorithms for deciding on speed limits in variable speed limit systems. Differences in the resulting traffic performance between the control algorithms are quantified by the use of microscopic traffic simulation. It is concluded that the defined objective for the algorithms have a decisive influence on the effects of the variable speed limit system.

The results from this thesis are useful for further development of variable speed limit systems, both with respect to incorporating cooperative features and by improving the speed setting control algorithms.
Acknowledgments

The research included in this thesis was carried out at the Swedish National Road and Transport Research Institute (VTI) and The division of Communication and Transport Systems (KTS) at Linköping University. The research has been financed by the Swedish Transport Administration through Center for Traffic Research (CTR), and in corporation with the Royal Institute of Technology (KTH).

First of all, I would like to thank my supervisors Jan Lundgren and Andreas Tapani for their guidance and for the possibility to freely explore my research field based on my own interests. I am grateful to Andreas who has supported me during my daily work with being there when needed for discussions, guidance and inspiration. Thanks to both Andreas and Jan for all your effort with reading and commenting on the text included in this thesis.

I am grateful to Xiaoliang Ma at KTH for valuable comments and a lucrative collaboration, and Bengt Hallström at the Swedish Transport Administration for his engagement in my research.

I have appreciated being part of the Swedish ITS Postgraduate School (NFITS) that has contributed with inspiring meetings, opportunities to meet colleagues from different parts of Sweden with similar interests, and interesting courses and study visits.

Thanks to all my colleagues at VTI and KTS for contributing with a great mix of inspiration to my research and a relaxed friendly environment. I am especially grateful to Fredrik, who has been a great roommate and friend during my years at VTI and KTS; thank you for our inspiring discussions over the years and for taking time to read and comment on this thesis. Thanks also to Henric and Emma that have made my days at the university extra joyful by being there, not just as good colleagues, but also as very good friends.

Finally, I would like to thank my family and my friends for your love and endless support. Last but not least I would like send my love to Tobbe for always being there, for putting up with my absent-mindedness during busy periods and for all your love, and to my daughter Saga who has been a great source to renewed energy when needed.

Norrköping, May 2014
Ellen Grumert
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Chapter 1

Introduction

The rapid development within the vehicle industry, along with a changed lifestyle in society as a whole, has led to an increased number of vehicles on the roads. This in turn has resulted in increased congestion on the road networks worldwide. The increased congestion have a negative effect on traffic efficiency with ineffective usage of roads, increased queuing of vehicles during congested periods and increased travel times, which in the end will be a great cost for the society. The trend is going in the same direction irrespectively of country with an increased demand for transportation both amongst private vehicles and amongst goods vehicles.

Apart from increasing congestion on the roads, the higher traffic flows leads to an increased risk of accidents and incidents. Many countries endeavor to decrease accidents and fatalities on the roads and work actively to make this happen. In Sweden the Vision Zero, ’Nollvisionen’ (Trafikverket, 2010), is a widely accepted concept aiming for improved traffic safety. The goal with the vision is to prevent fatal and serious personal injuries by taking all possible actions in order to achieve this. The vision accepts that nothing such as the perfect person exists and as a result of this, accidents will occur, but it does not accept serious personal injuries. The ideas behind the vision have also been utilized in other countries and today safety related issues are a big part of research in the transportation field.

The environmental problems caused by modern society are another well-known and discussed topic. Governments, scientist etc. all over the world are trying to work together to find solutions to the increasing environmental problems. The transportation field is a big
part of the problem with a large fossil fuel dependence and increasing pollutant emissions. The growing amount of vehicles are resulting in increased environmental impacts. Apart from this, problems with congestion as a result of the higher traffic flows makes the environmental impacts increase even more.

1.1 Intelligent transport systems and cooperative systems

One area, which is believed to have great potential impact on road safety, environmental issues and traffic efficiency, is Intelligent Transport System (ITS). The definition of ITS is according to the European Commission (2009): ‘Intelligent Transport Systems (ITS) means applying Information and Communication Technologies (ICT) to the transport sector. ITS can create clear benefits in terms of transport efficiency, sustainability, safety and security, whilst contributing to the EU Internal Market and competitiveness objectives.’ The vehicle actuated traffic light is a good example of an early ITS, which has the purpose to avoid congestion and accidents, by managing the traffic flows in intersections. Other examples are intelligent speed adaptation, variable message signs, etc. The early ITS are systems that are standalone, i.e. they are communicating in one direction, and where communication of information from the vehicles is not possible. The aim with the systems is to give the driver information or advice in order to enhance safety and efficiency.

Both traffic operators and vehicle manufacturers have a strong interest in ITS, and systems and technologies supporting ITS have been developed and deployed all over the world. This in turn has resulted in that many research projects have been focusing on ITS. One of the first big project within ITS was PROMETHEUS, (Diebold, 1995). The project started in 1986 with several project partners from the vehicle industry. The focus within the project was therefore on the vehicle side. Many of the ideas within the project were related to something that were later going to be called cooperative systems, where information regarding vehicles and traffic states could be communicated to other vehicles and information centers. Compared to the early ITS, the systems enables the vehicles to send and receive information from and to surrounding vehicles, and to send information to the infrastructure. The additional information flow could be
1.1. Intelligent transport systems and cooperative systems

used for enhancement of already existing information, resulting in improvements for the individual vehicles as well as for the whole traffic system. The problem at that time was the limited technology available, and many of the ideas within the project remained as just ideas.

Since PROMETHEUS in the 1980’s, the communication technologies has had a tremendous development, resulting in the introduction of cooperative systems. Thereby, the systems has taken another step in the direction towards fully autonomous, or self-driven vehicles. Today, the idea of having an autonomous vehicle driving on the roads in a near future has become a main target within many projects all over the world.

The idea behind cooperative systems, compared to the more ‘traditional’ ITS, is to increase the amount of real-time information given to the driver by two-way communication between vehicles, and between vehicles and the infrastructure. Also, the information given to road maintenance operators and the road authorities for prediction of future conditions on the roads could be improved by exchange of real-time information.

Today, many cooperative system only exists on a conceptual level, i.e. they have not been implemented under real world conditions but are only prototypes proposed in different projects. The reasons for this is mainly a high production cost together with the uncertainty of the actual benefits of the systems. Even so, the importance of deployment of cooperative systems are highlighted through action plans, forums, standardization organizations, etc. There is a strong need for evaluation of cooperative systems prior to actual deployment in order to be able to predict the potential benefits of the systems, and thereby speed-up the deployment process. To be able to evaluate a cooperative system prior to actual implementation a modeling approach of the cooperative system is needed. The modeling of the cooperative systems does not have to meet the level of details of a final implemented cooperative system, but should be representative for how the cooperative system will behave under real world conditions.

The focus in this thesis is on a cooperative variable speed limit system proposed as an extension to an existing variable speed limit system. A variable speed limit system consists of connected gantries on the road and detectors used for lowering the speed limits motivated by the traffic conditions on the road, and often with the objective to decrease the number of accidents and to increase traffic efficiency. The resulting recommended or compulsory variable speed
limits are displayed to the drivers via the gantries. Variable speed limit systems exists today and are already implemented in different parts of the world, such as in the UK (Highway Agency, 2007) and the Netherlands (van den Hoogen and Smulders, 1994). Evaluations of these systems indicate benefits in terms of safety, system efficiency and reduced exhaust emissions. By adding a cooperative part to these systems the benefits could be further enhanced. The idea is that the variable speed limits, displayed at the gantries, are communicated directly to each vehicle equipped with the system. The speed limits given to each vehicle is individual, i.e. it is based on the vehicle’s speed, the speed on the variable speed limit sign in front of the vehicle and the vehicle’s position on the road.

1.2 Aim and contribution

The overall aim of this thesis is to investigate the potential benefits of incorporating infrastructure to vehicle communication and autonomous control to an existing variable speed limit system. We show how such a cooperative variable speed limit system can be modeled and evaluated by the use of microscopic traffic simulation. Further, we compare four control algorithms for deciding on speed limits in variable speed limit systems. Differences in the resulting traffic performance between the control algorithms are quantified by the use of microscopic traffic simulation. The results from this thesis are useful for further development of current variable speed limit systems, by incorporating cooperative features and by improving the control algorithm included in existing systems. The thesis includes the following contributions:

- A survey to put cooperative systems into its context, covering projects related to cooperative systems in Europe, U.S. and Japan.

- Modeling of a cooperative variable speed limit system as an extension to an existing variable speed limit system.

- An evaluation of the cooperative variable speed limit system using microscopic traffic simulation, showing the effects on traffic performance and environmental issues.
1.2. Aim and contribution

- A quantification of differences in the resulting traffic performance between four control algorithms for calculating the speed limit in a variable speed limit system.

- An investigation of the appropriate approach for modeling of merging behavior under congested situations within a microscopic traffic simulation tool.

Parts of the contents of this thesis have been presented in a number of publications, summarized below;


The cooperative variable speed limit system proposed in paper 5 is the result of further development of a previously introduced cooperative variable speed limit system presented in paper 2-4.

The author of this thesis has been the main contributor to all the papers presented above, both as a main author, and with respect to research planning, modeling of the cooperative variable speed limit system, performing simulations and analyzing of the results.
Chapter 1. Introduction

The contents of the thesis have also been presented by the author at the following conferences:

- Transportforum, Linköping, Sweden, January, 2012
- The Eighth International Conference on Traffic & Transportation Studies (ICTTS’2012), Changsha, China, August 2012
- Nationell ITS konferens, Stockholm, Sweden September, 2012
- SUMO user conference 2013, Berlin, Germany, May, 2013
- Nationell konferensen i transportforskning, Gothenburg, Sweden, October, 2013
- Transportforum, Linköping, Sweden, January, 2014

1.3 Outline

An overview of cooperative systems including a summary of some of the most important projects in the area are presented in Chapter 2. Chapter 3 describes microscopic traffic simulation as a method used for evaluating intelligent transport systems. In Chapter 4 variable speed limit systems are described. Studies of already existing variable speed limit systems are presented, taking into account both field studies and traffic simulations studies. A cooperative variable speed limit system is modeled and evaluated in Chapter 5. In Chapter 6 four control algorithms, used in variable speed limit systems, have been compared. Drawbacks and benefits for the different algorithms are presented. Finally, Chapter 7 discuss the most important results from this thesis, as well as directions for further research.
Chapter 2

Cooperative systems

The transportation field has gone through some big changes during the last decades. Increased travel demand, along with a limited infrastructure, has led to congested roads and more accidents all around the world. The focus on Intelligent Transport Systems (ITS) has increased along with this development and lots of money have been given to research projects in the transportation field. Rapid changes and developments in communication technologies have put further attention on the development of ITS. Lately, cooperative systems have been developed as an extension to the traditional ITS. Cooperative system makes use of communication technologies for exchange of information between vehicles and between vehicles and the infrastructure. The information could be used for improving conditions on the road by increasing the awareness of the surrounding environment.

In this chapter an overview of cooperative systems is made together with a presentation of different types of projects carried out within cooperative systems in Europe, U.S. and Japan. In Section 2.1 an introduction of cooperative systems is made. Section 2.2 gives a summary of different types of cooperative systems/applications presented and discussed in many of the projects. Some of the most important issues when deploying cooperative systems are discussed in Section 2.3. Projects carried out within cooperative systems in Europe, U.S. and Japan are presented in Section 2.4. Finally, Section 2.5 gives an introduction to methods used for evaluation of cooperative systems prior to real-world implementation of the systems.
Chapter 2. Cooperative systems

2.1 Definition of cooperative systems

The European Commission (2009) has provided the following definition for ITS: ‘Intelligent Transport Systems (ITS) means applying Information and Communication Technologies (ICT) to the transport sector. ITS can create clear benefits in terms of transport efficiency, sustainability, safety and security, whilst contributing to the EU Internal Market and competitiveness objectives. To take full advantage of the benefits that ICT based systems and applications can bring to the transport sector it is necessary to ensure interoperability among the different systems throughout Europe at least.’

A good example of an early ITS is the vehicle actuated traffic light, which has the purpose to avoid congestion and accidents, by managing the traffic flows in intersections. The early ITS are standalone systems, i.e. they have one purpose and are communicating in one direction, giving the driver information or advice.

Cooperative systems aim to take another step towards an information, advice and communication aided environment on the roads. One idea is to make vehicles ‘talk to each other’. An on-board unit inside the vehicle should be able to send and receive information from surrounding vehicles with the use of already existing technologies and by the development of new technologies. This type of communication is called vehicle-to-vehicle communication and is often abbreviated to V2V communication. Another type of communication that can be used within cooperative systems is the vehicle-to-infrastructure communication and infrastructure-to-vehicle communication, often abbreviated to V2I and I2V communication, respectively. Meaning that the vehicles are able to send and receive information from roadside units. Another term that often is used is V2X communication, meaning both V2V and V2I communication.

Cooperative systems have been provided with the following definition by the European Commission (2009): ‘Cooperative systems are ITS systems based on vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-infrastructure (I2I) communications for the exchange of information. Cooperative systems have the potential to further increase the benefits of ITS services and applications.’

Technology like wireless communication etc. have been more and more widespread. Today most of the vehicle owners, in large parts of the world, have smartphones for exchange of information. This kind of equipment could easily be extended to include exchange of in-
formation between vehicles and vehicles and the infrastructure. Also equipment installed inside the vehicle has become more and more common. This has made the V2X communication easily accessible and cooperative system has become a large focus area for the vehicle industry and as part of research projects all over the world.

2.2 Applications

Projects involved in cooperative systems are often developing, improving or evaluating some type of applications. An application refers to a function using V2X communication to reach a specific goal, for example increasing safety by warning the driver about accidents further downstream. The applications could be either advisory, i.e. acting as pure informatorial systems, or autonomous, i.e. built-in systems working without interaction with the driver.

When many applications are composed into a larger system, working together or as standalone systems, they are often collected into something referred to as a platform. The main goal with making use of a platform is that the applications can be added at different points in time and they can work together independent of developer/distributor, i.e. they are interoperable in time and among distributors.

In many of the large projects within the development of cooperative systems more than one application are introduced. The applications have been divided into different categories and the categories might be slightly different depending on the project. A summary of the main categories covered in many projects, as well as examples of applications included in each category, is presented in Table 2.1.

The applications presented in Table 2.1 can be categorized in many ways depending on the main purpose. In-vehicle speed advices can for example be used to increase traffic efficiency in traffic management applications with the main purpose to harmonize the traffic flow and to avoid congestion. This is done by proposing appropriate speed limits to the vehicles by inclusion of I2V communication of legal or variable speed limits, or by V2V communication of appropriate speed limits based on the surrounding vehicles speeds. But, the in-vehicle speed advices can also be seen as a safety application since it reduces the risk of an accident by harmonizing the traffic flow and keeping the vehicles speed close to legal or variable speed limits on the road. An-
Chapter 2. Cooperative systems

### Table 2.1: Categorization of proposed applications in some of the projects presented in Section 2.4, including examples of applications.

<table>
<thead>
<tr>
<th>Category</th>
<th>Applications</th>
</tr>
</thead>
</table>
| Traffic and management solutions /traffic efficiency | • Routplanning and re-routing  
• In-vehicle display of dynamic traffic signs and speed advice  
• Provision of input data for Traffic Management Centers  
• Dynamic lane allocation  
• Cooperative lane changing/merging  
• Traffic prioritization  
• Intermodal journey planning  
• Dynamic tolling/congestion charging  
• Traffic information service  
• Intersection management/Traffic light optimization  
• Cooperative adaptive cruise control  
• Cooperative vehicle highway automation system |
| Logistic and Freight Management               | • Parking zone management  
• Truck access control  
• Dangerous goods management  
• Multi-modal freight transport planning |
| Safety                                        | • Safe overtaking  
• Emergency broadcast  
• Accident/incident warning  
• Pre-crash mitigation/collision warnings  
• Coordinated breaking  
• Hazardous warning  
• Weather/road condition warning  
• Roadwork information  
• Road intersection warnings  
• Traffic congestion warning  
• Safety distance  
• Curve/turn warnings  
• Vulnerable road user warnings  
• Wrong way driving  
• Post-crash warnings  
• Car breakdown warning |
| Maintenance                                    | • Sensor calibration  
• Remote diagnostics |
| Infotainment, business and deployment          | • Point of interest notification  
• Parking management  
• Car rental/sharing assignment/reporting  
• High speed internet access  
• Stolen vehicle alert  
• Remote personal data synchronization  
• Vehicle software provisioning and update |
| Environmental issues                          | • Eco driving  
• Eco trip planning (pre, post and under trip)  
• Eco professional driver coaching/eco fleet planning and routing  
• Eco traffic management |
2.3 Issues

Other example is the road condition information/warnings, which is a typical safety application with the aim of helping the driver to adapt to the conditions on the road. But, if used as V2I communication to a traffic management center it could also be used for maintenance of the roads by detecting road sections where the conditions are bad. There is a number of other examples of applications that can be divided into many different categories. An improvement in one category does not necessarily exclude an improvement in another category, but sometimes the goals are reluctant. Such can be the case when improving efficiency by cooperative adaptive cruise control. This might lead to very small time gaps between vehicles and in case of accidents or failure of systems this will be bad with respect to safety.

Finally, the applications presented above can be based both on V2V, I2V and/or V2I communications. One example is the intersection application that can make use of I2V communication by communicating traffic light restrictions or V2V communication by sending warnings about vehicles that are not yet visible in the intersection.

2.3 Issues

In order to deploy cooperative systems within Europe and the rest of the world and get it to work in an interoperable and efficient way some issues needs to be considered and carefully treated. The most important issues have been listed by and discussed in CVIS (2010a) and are also discussed below.

Standardization

For cooperative systems to work efficient and in an interoperable way, not only within one platform but in cooperation with other platforms, some kind of standards are needed. These standards should include not only standardization of applications, but also standardization of the technology used, standardizations of the facilities used, and so on. In order to cover all aspects, and for the final set of standardizations to be useful for all stakeholders, it is important to include all relevant stakeholders early in the process. It is also important to have a close cooperation between regions and countries in other parts of the world in order for the cooperative system to be interoperable worldwide. The standards should try to minimize any extra work needed when
implementing a cooperative system independently of type of vehicle used or infrastructure environment applied.

User acceptance

Some of the projects that have been carried out today have been focusing on evaluation and analysis of the applications and systems within cooperative systems. The main focus during the evaluation of the applications and systems has been on the usefulness for the traffic network and if applications/systems covers its purpose, rather than on how useful the application is for the users.

Evaluations of applications and systems with respect to usefulness for the end-user are as important as the functionalities for the application/system to become a future success. It is important that the cooperative system fulfills its purpose for all users. This involves utility and usefulness for both drivers and the road authorities/managers of the systems. To make the system useful, consideration should be given both to the type of applications and the type of drivers that the system focuses on.

In order for a system to work well and serve its purpose it is of course also a question of how many vehicles are equipped with the applications. Some applications, such as warnings systems, might be independent of the penetration level. At least if the warnings are communicated to the vehicle through I2V communication via a traffic management center. Whereas other application might be very dependent on the penetration level to give a desired effect.

Security and data privacy

Cooperative systems does often have the aim to be developed within open platforms where everyone with some basic knowledge has the possibility to add applications etc. The advantage with an open platform is that the goal of having interoperability is speeded up, and different kind of stakeholders can easily add their applications to the system. When keeping this high level of openness it might be hard to keep a good level of security and privacy. Therefore solutions for protection of users and producers needs to be developed.

In a questionnaire done by CVIS (2010a), 77% answered that they did care about if the system was invading their privacy. It is therefore important to find a way to protect private users from exposure
of sensitive data. It is also important to protect providers of applications/platforms against vicious attacks, false messages and so on.

Legal issues and liabilities

It is of great importance to clearly state who has the final responsibility in situations that might lead to violation against the law. When the vehicles get more and more directed by the cooperative system the driver might feel that the responsibility for driving is lower than before. It is therefore important to make the driver aware of that he/she is still the person who has the final responsibility when something happens. The cooperative systems are today only being seen as a guiding system to the (standalone) driver, even though the systems might be partly or fully autonomous in the future. This will even further magnifying the importance of clarifying how has the responsibility in case of an incident or accident.

In some cases the service provider might be the responsible part of an incident/accident, i.e. wrong or missing information might be transmitted to the driver. In this case, the local authority might want to be able to locate the service provider and monitor the information sent out by the service provider in order to determine who has the responsibility for the missing/false information.

Multi stakeholders cooperation

Cooperative systems involve many different stakeholders with various goals. It is therefore important that all relevant stakeholders are included in the process of the development and deployment of cooperative systems, in order to get interoperability of the systems. The different stakeholders involved are summarized below:

- Developers:
  - Vehicle manufacturers
  - Equipment manufacturers
  - Research institutions
  - Software developers

- Users:
  - Local authorities
  - National road authorities
  - Road operators
Chapter 2. Cooperative systems

- Freight operators
- Public transport operators
- Private road users

• Promoters:
  - Users organizations
  - Transport organizations
  - Service providers.

Cooperation between stakeholders is an important element in the ongoing standardization process.

Conclusions

All the issues discussed above are important and relevant for the development and deployment of cooperative systems. Many stakeholders are involved in one or more of the issues. In order for cooperative systems to become ‘cooperative’, not only for that specific application but also among applications and in different parts of the world, the issues discussed in this section needs to be taken serious. The main issues, the affected stakeholders and proposed solutions as presented by CVIS (2010a) are summarized in Table 2.2.
### Table 2.2: Main issues regarding implementation of cooperative systems, including affected stakeholders and possible solutions according to CVIS (2010a).

<table>
<thead>
<tr>
<th>Issues</th>
<th>Affected stakeholders</th>
<th>Solution</th>
</tr>
</thead>
</table>
| Standardization             | • Vehicle and telecom industry (world wide)  
• Authorities               | • Find interoperable standards by cooperation between standardization organizations, and standardization organizations and the industry |
| User acceptance             | • Vehicle users  
• Road authorities             | • Questionnaires to affected persons  
• Studies  
• Field tests                 |
| Security and privacy        | • Vehicle users  
• Service providers             | • Well-designed architecture  
• “Future-proof” solutions to ensure that platforms stays secure when technology changes |
| Legal issues and liabilities| • Vehicle users  
• Service providers             | • Stakeholders awareness regarding responsibility  
• Consideration of issues before deployment  
• Information about responsibility  
• Monitoring of transfer data to prove inconsistencies (proof service providers mistakes) |
| Multistakeholders cooperation| • Telecom industry  
• Authorities  
• Car industry  
• Etc.                     | • Inclusion of all stakeholders  
• Funded projects bringing stakeholders together  
• Existence of a good business plan for developing of cooperative systems |
2.4 Projects in cooperative systems

Many projects in ITS have been focusing on cooperative systems. Some of the earliest ones, like PROMETHEUS in Europe, VII in U.S. and AHSS and ASV in Japan indicated the importance of cooperative systems already in the 1980’s and the 1990’s. VII started in 2003 and thereby somewhat later than the others.

Since then the communication technologies which can be used within the area have had a tremendous development. During the following years many projects have been, carried out within the area of cooperative systems, both on national level and international level.

In this section we present many of the most relevant projects for the development of cooperative systems in Europe, U.S. and Japan. The organizational structure of the funding and a summary of many of the projects carried out in Europe, U.S. and Japan respectively are given. Also a number of cooperations carried out between the countries/regions are presented. Finally, a comparison of the organizational structure, type and size of projects, focus areas, etc. are made between the different countries/regions.

Europe

Europe has been promoting and supporting the development of projects related to ITS and cooperative systems for a long time. Many projects have been funded by the European commission through the Fifth, Sixth and Seventh Framework Programmes (European Commission, 2010).

One of the first big projects within ITS was PROMETHEUS, (Diebold, 1995), which stands for Program for European Traffic with Highest Efficiency and Unprecedented Safety. The project started in 1986 and was part of the European Research Coordination Agency (EUREKA). The project partners included only vehicle manufacturers and the focus within the project was therefore on the vehicle side. One of the difficulties with the PROMETHEUS project was the technologies available at that time, which limited the use of the results from the project.

Some of the most exhaustive projects in Europe in later years are projects like CVIS (CVIS, 2010a), SAFESPOT (Safespot, 2010), COOPERS (COOPERS, 2010a,b) and PreDrive C2X (Schulze, 2010; Enkelmann et al., 2008). These projects have been carried out within
the Framework Programmes. The results from these projects have been used in many other projects and the European Commission has used the projects as a base for further development.

Another project, that is of great importance, due to the coverage, is the COMeSafety (Bechler et al., 2010; COMeSafety, 2010) project. This project collects the results from some of the largest projects, both within and outside of the Framework Programmes. Some examples of included projects are COOPERS, CVIS, SAFESPOT, SEVECOM, GeoNet, FRAME, E-FRAME, SafetyForum and Car-2-Car Communication Consortium, which are all Framework projects. Apart from the projects mentioned above, some of the standardization organizations have also been involved in the COMeSafety project: CEN, ISO, ETSI, IEEE and IETF. Projects outside of Europe have also been considered in the project. The project has been looking at questions regarding the requirements for an overall framework within cooperative systems and an open and interoperable architecture for the systems.

Many projects within the Framework Programmes are not as big as the ones mentioned above, but they are still important and play an important role in the development and deployment of cooperative systems.

The areas of interest within the projects might sometimes overlap especially for the more comprehensive projects. Figure 2.1 gives an overview of how the projects on European level are connected.
Chapter 2. Cooperative systems

Figure 2.1: An overview of how the projects in Europe are connected. The projects can be divided into development projects, testing projects, evaluation and deployment projects and summary projects, which collects the most important results from other projects. Some of the more comprehensive projects might include both development, and testing, evaluation and deployment.

Apart from the projects in the Framework Programmes, many national projects within Europe have also been carried out within the cooperative systems area. These projects are important, especially for the nation in question. The nation specific projects can address issues like specific laws restricting the systems or other nation specific questions that might be of interest during the development of the systems.

Table A.1-A.5 in Appendix gives a summary of projects within cooperative systems carried out in Europe and on national level, together with their main focus area. The summary is based on the
2.4. Projects in cooperative systems

Also the manufacturers are developing new systems covered in the cooperative systems area, and forums including manufacturers have been developed, to take care of and promote their interests. There has been cooperation between the forums and some of the projects, especially with projects on EU level. Some of the forums include only (or mostly) manufacturers, such as Car-2-car Communication Consortium (2007, 2010), which is the ‘voice’ of the vehicle industry, and others try to bring together different stakeholders and projects, like ERTICO (2010a), for cooperation and knowledge sharing. The Car-2-Car Communication Consortium has been included in a lot of the largest projects in Europe and their opinion is seen as important since they represent the vehicle industry.

Apart from all the projects carried out within Europe there has been a number of initiatives and actions taken during the years such as the action plan (European Commission, 2008). The action plan aims at accelerate and coordinate the deployment process of ITS in Europe. The focus is on road transport but interfaces with other modes are also included.

U.S.

The U.S. Department of Transportation, U.S. DOT, were early to support and promote the development of cooperative systems. Some large projects have been performed within the area, such as VII/IntelliDrive (The VII Consortium, 2009; U.S. DOT, 2009), VSC (Laberteaux, 2006; Shulman and Deering, 2004; Shulman, 2009) and EEBL (Shulman, 2009). Today, a big ITS program and a strategic research plan are in process, organized by the U.S. DOT. Within the program, the extensive project, VII/IntelliDrive, is included.

The VII/IntelliDrive project is the far most extensive project in U.S. The U.S. DOT is not only funding the project, but also supporting the project with administrative help etc. Apart from U.S. DOT, manufacturers and American Association of State Highway and Transportation Officials and their local agencies are also included in the project.

The research program ITS Joint Program Office, ITS JPO, (U.S. DOT, 2010b), is coordinated by the Research and Innovative Technology Administration (RITA). The purpose with the ITS program is to improve and continue the development and deployment of ITS by
research, operational field testing, technology transfer, training and technical guidance. The program is investing in projects related to ITS, and among them some projects that are focusing on cooperative systems.

Table A.6 in Appendix gives a summary of projects within cooperative systems carried out in U.S., together with their main focus areas. The summary is based on the report by Grumert (2011).

Organizations and forums have also been created along the way. The aim has been to bring together different stakeholders, and to create a platform for research and development within cooperative systems, in order to build up cooperation’s and relationships between the stakeholders.

CAMP, Crash Avoidance Metrics Partnership, (Laberteaux, 2006; Shulman and Deering, 2004; U.S. DOT, 2010c) is an organization composed by some of the vehicle industry operators. The organization has been part of many projects where development of applications and technologies has been in focus. CAMP can be compared with Car-2-Car Communication Consortium in Europe, but with not as many partners as Car-2-Car and with more focus on funding of projects. CVPC (2010) and CVTA (2010) brings together different stakeholders within the area of cooperative systems. CVPC (Connected Vehicle Proving Center) is a program led by the academia and the industry. The aim of the program is to connect researchers and developers in order to accelerate the deployment of new technologies within cooperative systems. CVTA (Connected Vehicle Association) is an association which connects different stakeholders. The association is working within the field of vehicle communications and opens up for cooperation between different stakeholders.

Apart from the stakeholders cooperations within the development and deployment of cooperative systems there is also a consortium, OmniAir (2010), focusing on the deployment of the 5.9 GHz Dedicated Short-Range Communications.

Finally, ITS America (2010) brings together both U.S. interests as well as worldwide interests within the area of ITS.

Japan

Japan has, during the years, had four strategy plans (Oku, 2010) for the development of ICT (Information and Communication Technology). Cooperative systems are a big part of this, since ICT technology
is used for building the systems and applications.

When the first plan was set out in 2001 there was a reformation of the governmental bodies in Japan. Five government ministries became four ITS-related ministries which have been working with ITS-related questions since then. The four governmental bodies are (ITS Japan, 2010):

- National Police Agency
- Ministry of Public Management, Home Affairs, Posts and Telecommunications (former Ministry of Posts and Telecommunications)
- Ministry of Economy, Trade and Industry (former Ministry of International Trade and Industry)

Already in 1989 the AHSS (Gee, 1997) project started with support from the government. Many other projects have also been performed with support from the governmental bodies, such as ASHRA (Gee, 1997; Schulze, 2006), Smartway (Schulze, 2006) and ASV (IATSS Research, 2006; Wani, 2006; Gee, 1997).

Some of the larger projects within cooperative systems in Japan are VICS (VICS, 2010) and ASV-IV (Wani, 2006). Both of them are extensive projects with a long history. The ASV-IV has been developed from the former ASV projects and the VICS project has been ongoing since 1995.

The main focus for many of the Japanese projects has been V2I communication, where Japan has been introducing applications not only on research level, but also on the market. The ASV (Advanced Safety Vehicle) project has during the two later phases (III and IV), been focusing on V2V communication, as well as V2I communication.

Table A.7 in Appendix gives an overview of the largest/most mentioned projects in Japan taken from Grumert (2011). It should be mentioned that Japan is the country where information regarding the projects was hardest to find. Therefore this table might miss out on some projects due to lack of information.

Apart from the projects, two forums/organizations have been of important in the process of bringing together different stakeholders, promoting ITS systems to the wider public and to support the standardization of the systems.

The ITS, info-communications forum (2010) was created in 1999. It is a forum for ITS activities, with the aim to bring together activ-
Chapter 2. Cooperative systems

Cooperation between stakeholders and cooperation over nations

Cooperation is seen as relevant in order to get an as fast and widespread deployment of the systems as possible. Both manufacturers and governments can benefit a lot from cooperation activities. The manufacturers can reach a larger market if the systems they produce and sell are interoperable and work cross-boarders, and the governments can ensure a faster and more effective deployment of the systems. This will hopefully result in increased safety and efficiency on the roads, as well as interoperable and useful systems. Liaisons and agreements has been signed between U.S. and Europe, and, Japan and Europe.

The European Commission and U.S. DOT have agreed on a joint declaration of Intent on Research Cooperation in Cooperative Systems (Stancic and Appel, 2009). This declaration states that both parties believes that cooperative systems can bring a lot of benefits, for both private road users and the public, in terms of safer, more energy efficient and environmentally friendly transport.

The cooperation is further strengthen through an Implementing agreement (Stancic and Appel, 2008) between the two parties. The implementing agreement includes settlements regarding cooperation in research and activities regarding Information and Communication Technologies (ICT) and especially the research on ICT applications for road transport (i.e. cooperative systems). Knowledge sharing is of special importance, and in particular between the standardization organizations and the automotive industry. It is believed that globally harmonized standards are essential in the process of deployment of cooperative systems.

Japan and the European Union have been in cooperation for a
long time. In 1991 they signed a joint declaration, with the purpose to strengthen the overall cooperation between EU and Japan since they both are strong industrialized countries with the same core values. In 2001 this was further strengthened via an action plan, which was a 10 years cooperation plan.

Japanese Information and Communication Technologies (ICT) companies located in EU have been part of the European research and development projects for a long time, especially in the Sixth Framework Programme. But cooperation with ICT companies located in Japan has been limited. As a result of that and in order to increase the EU - Japan and South Korea cooperation in the ICT area the COJAK project was carried out (European Commission, 2010; EuroJapan-ICT.org, 2010). The importance of harmonized standards, architecture and application was highlighted within the project.

Another type of cooperation is done between the organizations ITS America, ITS Japan and ERTICO. They have been working on bringing together relevant stakeholders within each region, but also by introduce cooperation across borders. The ITS world congress is a joint effort between the three organizations. These three organizations are important in the process of exchange of information within the different regions.

Cooperation on national level is also of great importance. A number of forums and initiatives with many different stakeholders involved has been developed both in Europe, U.S. and Japan.

Finally, cooperation between stakeholders inside the projects is important to cover the issues regarding interoperability and to take into account different viewpoints.

Comparison between countries/regions

All, or most of the projects presented in this chapter, irrespectively of country or union, has the main goal to increase safety and efficiency in the traffic. Higher traffic demands in all countries/regions has resulted in congestion and increased number of accidents. The believes in both EU, Japan and U.S. is that cooperative systems can contribute to decrease the number of injuries (increase safety), increase the efficiency on the roads and make the traffic flows more stable and diversified. The focus within the projects this far has been on the technologies used, frequency bandwidth, the system architecture
Chapter 2. Cooperative systems

and the applications. The applications in the projects regardless of country or union are often split in safety applications and efficiency application. In some of the projects management applications and infotainment applications have also been considered.

During the later years, when the environmental issues have become more and more important and pollutions and exhaust emissions are increasing, more consideration has been taken to the reduction of environmental impacts. The believes is that cooperative systems can contribute to a reduction of the environmental impacts as well. Europe, as well as U.S., has started projects with the main purpose to develop applications that contributes to reduction of pollutions. In Europe the projects EcoMove, FREILOT and INTIME, part of the Seventh Framework Programme, are focusing on these issues and in U.S., the sub-project AERIS, part of the IntelliDrive project, has been focusing on environmental issues. In Japan the consideration regarding the environmental impacts has not been as explicit as in U.S. and Europe. No specific project has been focusing on the environmental impacts, even if the environmental impacts is included indirectly in some of the project, with for instance route guidance applications, warnings of congested roads, etc. Some of the projects, in Japan, have also mentioned the need for decreased pollutions.

Europe have carried out a large amount of projects, most of them sponsored by the European Commission, but also projects on national level are common. Some of the projects are therefore very closely related to each other and there might be overlaps between them. This means that Europe has a wide range of viewpoints and many different approaches have been and are investigated and evaluated regarding cooperative systems, but it can also mean that there are too many projects resulting in that it can be harder to find the important results among the projects. It is also possible that the projects closely related to each other compete instead of cooperate. The aim and purpose with the projects within Europe have moved from development and research of new applications and technologies to evaluation and deployment.

In U.S. there is one large project, funded by the government, VII/IntelliDrive, and some smaller projects supported by the government or as CAMP projects, which is a partnership of seven manufacturer. The impression is that the projects are fewer in the U.S. The IntelliDrive project is the far most extensive project and it is also part of the U.S. government strategy research plan in the area of cooperative
2.4. Projects in cooperative systems

There are a few big leading stakeholders in top of the research and development, within the area of cooperative systems. The strategy in U.S. is differentiating a bit from the strategy in Europe. The benefits from having one strong leading project funded by the government together with CAMP projects (often projects in cooperation with U.S. DOT), which is a complement to that, is that it makes the structure simple and it is easy for the government to keep track on the process. It is also easy for the government to steer the projects in a desired direction. On the other hand, if there are only a few stakeholders involved there might be aspects left out and stakeholders not involved might feel overlooked. The main focus within the projects has early been to develop functional applications that could actually be used on the roads after development. Also in U.S. the trend has moved away from the development of applications to deployment and testing.

In Japan, it is harder to find information due to language difficulties and less information on the project homepages, and it is thereby harder to evaluate the projects. The feeling is that the documents related to the projects doesn’t become public as often as they do in Europe and U.S. The main focus in Japan has been on the whole chain from a prototype application to actual deployment of the application. This is demonstrated by fewer projects and with projects building upon each other, such as ASV and AHSRA. Many of the largest national projects in Japan are driven by the four ITS-related ministries, which makes it harder to get a clear picture of the strategies and the projects. Besides the national projects, the vehicle industry is developing applications and technologies related to cooperative systems, often developed only with one manufacturer included.

Japan did early have more focus on deployment and to get the systems out on the market, compared to Europe and U.S. Both U.S. and Europe have been focusing more on research and development and they have only recently begun to investigate in deployment of the systems more thoroughly.

All of the nations (U.S., Japan and Europe), have a strong governmental support or in Europe’s case via the European Commission. The governments and the European Commission are funding many projects and supporting the projects with huge amounts of money, which shows how much the countries believes in cooperative systems and the further development in the area.

Cooperations across nations is seen as important in EU, U.S.
and Japan. The cooperations among nations/regions are supported through signed agreements. The intention is clear but even so there might be differences in the governmental structure, prioritization of issues, as well as cultural differences, that can complicate the cooperations. There might also be competition issues related to cooperation and it is possible that information cannot be revealed due to confidentiality, especially since the vehicle industry are included.

2.5 Evaluation of cooperative systems

Many of the systems proposed in projects and by vehicle manufacturers have not yet been developed, or at least not yet been implemented, on the market. Therefore, one can only imagine how much influence the systems will have on the individual vehicles and the whole traffic system. The usefulness of a specific cooperative system is sometimes also dependent on the number of equipped vehicles. Therefore, investigations of how different penetration rates of in-vehicle systems and roadside units affect the overall traffic flows is important to consider.

Many different methods can be applied for prediction of the usefulness of a not fully developed cooperative systems. The choice of method is dependent on the purpose of the cooperative system, the type of evaluation needed, the expected effects, etc. Most of the time more than one method is needed to give an overview of the effects the cooperative system will have on the driver, the surrounding environment, the traffic system and so on.

For the system to be successful, the end-user, often the driver but also authorities and road operators, needs to find the system useful. For these kind of evaluations driving simulator studies and questionnaires are best suited. Driving simulator studies tries to build-up an environment as close to reality as possible inside a driving simulator and evaluate the effect the system will have on the driver. The studies usually focuses on the drivers perception of the systems and how the driver react with the system in use in the vehicle. Observations from the simulator study are used for identification of the driver behavior. Questionnaires during and after the simulator study are used for identification of the driver perception of the system. This is useful to get an idea of the user needs before implementing a system and to see if the user act as expected to the information given by the system. Improvements could thereby be done before the actual system
is out on the market, increasing the probability of a future success of the system with respect to end-users willingness to buy and use the system.

For evaluations of the system performance on the total traffic system different type of traffic simulation studies can be useful. A road stretch, or a larger network, built-up in a computer simulation environment are investigated by applying vehicles or vehicle flows to the considered test area. Assumptions regarding the vehicles in the simulation and the surrounding environment are made to correspond to reality as much as possible. Traffic simulation studies are suitable when a cooperative system have not been implemented and deployed under real world conditions, and when a first investigation of the system is requested to give indications of the traffic system performance. Traffic simulation can be used both for testing of finalized cooperative systems, where the properties are already defined, and for developing new or improved cooperative systems, where the properties are changed or modified during the simulation process. Additionally, different traffic scenarios can be applied for investigation of how the cooperative system are affected by different road conditions. Effects like emission calculations and effectiveness of the cooperative system with respect to travel time, speed levels, etc. could be investigated. In the case of microscopic traffic simulation, also individual vehicle behavior such as acceleration levels, effects with different type of drivers (aggressive vs. non-aggressive drivers), and so on could be investigated.

An other method, useful for both perception and system performance are Field Operational Tests (FOTs). In FOTs the cooperative system is implemented in vehicles under real-world driving conditions, either on a controlled stretch, or as part of ordinary vehicles driving in normal traffic conditions, i.e. on regular roads. These studies can result in identification of system performance considering technical aspects, as well as studies of driver behavior and driver perception via interviews, daily dairies, etc.

None of the above mentioned methods represent a 'true' reality with the implemented cooperative system, but are rather a model of the 'true' reality set up to represent reality as good as possible under conditions set out by the specific method in use. All the above mentioned methods have their own benefits and drawbacks.

In this thesis traffic simulation is used for modeling and evaluation of a cooperative variable speed limit system.
Chapter 3

Microscopic traffic simulation for modeling of ITS

Traffic simulation is commonly used for investigation of the performance of traffic systems. One area where traffic simulation is believed to be useful is for evaluation of the effects of ITS, both prior to actual implementation and for implemented systems where the need for further investigations of the system properties, different surrounding environments, etc. is needed. A number of traffic simulation tools exist with different level of detail. In this chapter some of the available traffic simulation tools are presented. The use of traffic simulation, and especially microscopic traffic simulation, for modeling and evaluation of ITS are discussed. In this thesis the microscopic traffic simulation tool SUMO is used for evaluation of the cooperative variable speed limit system presented in Chapter 5 and for comparison of the control algorithms presented in Chapter 6. SUMO is therefore described in more detail. To evaluate environmental impacts of ITS using traffic simulation an emission model is needed. The emission model used must be able to reflect the effects of the traffic and system dynamics on the resulting emissions. A short overview of existing emission models is given.

Section 3.1 gives a classification of the different types of traffic simulation models. In Section 3.2 different microscopic traffic simula-
tion tools are described. Section 3.3 gives a more in-dept description of the microscopic traffic simulation tool SUMO. A short review of existing exhaust emission models is presented in Section 3.4.

3.1 Classification of traffic simulation models

Traffic simulation models are often categorized into three levels based on the desired level of detail in the model: macroscopic-, mesoscopic- and microscopic traffic simulation.

In a macroscopic traffic simulator the traffic flow is usually represented by differential equations representing the speed, volume and density; see e.g. Lighthill and Whitham (1955) and Messner and Papageorgiou (1990). The fundamental relations used in macroscopic traffic simulation are the conservation of flow, i.e. vehicles can’t suddenly disappear or appear, and the fundamental relationship between flow, speed and density, \( q = k \cdot v \). To solve the differential equations, a discretization in time and space is made. The considered road is divided into segments and for each of the segment speed, volume and density are calculated. The simulation is based on the transmission of traffic flow between these segments.

In a microscopic traffic simulator the vehicles are modeled individually and the longitudinal and latitudinal movements of each vehicle are modeled with a car-following and a lane changing model respectively. Vehicle and driver specific parameters are used as input to the models. Example of such parameters are reaction time of the driver, maximum acceleration ability, gap acceptance to the vehicle in front etc. The interaction between the vehicles in the simulation is based on the car-following and lane changing model. Each simulated vehicle is contributing to the total traffic stream from where mean flow, mean density and mean speed can be computed.

A mesoscopic traffic simulator is trying to capture some of the behaviors and interactions of the individual vehicles but with a lower level of detail. This allows for simulating larger networks than with a microscopic traffic simulator, but with more details included than in a macroscopic traffic simulator. This can be achieved by describing and simulating individual vehicles but where the calculations of vehicle dynamics are based on conditions on a macroscopic level.

The appropriate type of traffic simulator used is dependent on the
3.2 Microscopic traffic simulation tools

When a low level of detail is required and a big network needs to be investigated a macroscopic traffic simulator is more efficient compared to the other two traffic simulators. On the other hand, if there is a need for modeling of individual vehicle behavior, a microscopic traffic simulator is more suitable. To be able to evaluate the resulting effect on the traffic system considering an individual vehicle level, such as the distribution of accelerations, a microscopic traffic simulator is needed. A drawback with using microscopic traffic simulation is that assumptions regarding individual vehicles need to be addressed and calibrated for the vehicle dynamics to reflect the reality well. Also, since the level of detail is very high the simulation time can become high with increasing simulation area and/or traffic demand. The mesoscopic traffic simulator is suitable when a larger network should be simulated, but still with requiring some level of detail with respect to the vehicle behavior. A trade-off is made between the size of the network and the level of detail for which the interactions and the behavior of the vehicles should be modeled.

ITS does often require control of individual vehicles within the simulations. Examples are intelligent speed adaption and intelligent cruise control where the speed of individual vehicles are adjusted based on the system output, route guiding systems which apply information to individually equipped vehicles, and different types of signal control systems reacting on approaching vehicles. Therefore, microscopic traffic simulation are often deemed suitable when evaluating ITS, since they are capable of modeling individual interactions of the vehicles within the simulation.

3.2 Microscopic traffic simulation tools

Many different microscopic traffic simulation tools are available, both commercial and open source, each of them with its own benefits and drawbacks. The most well-known tools have usually been developed over several years, and have been continuously improved and adapted to new type of traffic behaviors.

A microscopic traffic simulation tool consists of two main core models, the car-following model and the lane changing model. The car-following model describes how a single vehicle in the simulation interact with vehicles in front, or in free flow if no vehicles are present in front of the vehicle, how the desired speed should be decided. The
lane changing model regulate if and how the vehicle should behave in case of a lane change situation. The underlying core models used are varying between different microscopic traffic simulation tool.

The lane changing model is commonly based on a set of rules, where the vehicle at the end decides if it is desirable or not to change lane based on, for example, gap to proceeding vehicles, acceleration needed to change lane, feasible path for lane changing etc.

The other main part of a microscopic traffic simulation tool is the car-following model. Some car-following models have been summarized in a historical review by Brackstone and McDonald (1999). One of the first car-following models is originating from the fifties as part of General Motors research, and has resulted in the GHR model named after the original authors Gazis, Herman and Rothery. The model has been extended and modified since the first version in the fifties with many different contributors over the years. The GHR model is a so called stimulus-response model. The acceleration of a vehicle (response) depends on some stimulus, which in the GHR case is the speed of the vehicle, the difference in speed between the vehicle and its leader, and the space headway between the vehicle and its leader. The acceleration of vehicle \( n \) at time \( t \) is calculated as

\[
a_n(t) = cv_n^m(t) \frac{\Delta v(t - T)}{\Delta x^l(t - T)},
\]

where \( v_n(t) \) is the speed of vehicle \( n \) at time \( t \), \( \Delta v(t - T) \) and \( \Delta x(t - T) \), is the relative speed and the relative spacing between vehicle \( n \) and its leader at time \( t - T \), where \( T \) is the reaction time. \( c \), \( m \) and \( l \) are modeling parameters. The model has been investigated many times during the years and different values of the model parameters have been proposed as the best set of parameters to fit with empirical data. Both microscopic and macroscopic relationships have been investigated. According to Brackstone and McDonald (1999), the GHR model are being used less frequently due to many contradictory findings regarding the model parameters.

Another type of model is the safe distance model, or collision avoidance model, where the idea is that the drivers tries to maintain a safe distance to the vehicles in front, and thereby avoid collisions. The model proposed by Gipps (1981) is one of the most famous versions of a safe distance model. According to Brackstone and McDonald (1999) the main advantage with this model is the realism of the model as a result of the directly measurable model parameters. But also a lot
of assumptions may be questionable, such as the assumption that a driver only consider one leader, and not looking further ahead, when adapting to its safe distance.

Psycho-physical, or action point models, uses thresholds under which drivers are assumed to change their behavior. The thresholds are based on relative speed and relative position. The driver adapt their speed based on how it perceive the speed difference between itself and the vehicle in front. One way to do this is to assume that a vehicle perceive the speed difference between itself and the vehicle in front based on the change of experienced size of the vehicle in front. When the relative speed is not longer perceivable the speed adaptation will be based on changes in spacing. Although, as mentioned in Brackstone and McDonald (1999), this model is seen as representing the everyday driving behavior best, the calibration of the thresholds and individual elements have not been successful. The authors therefore mean that it is hard to prove the usefulness and the realism of the model. The most widely used psycho physical models are presented by Wiedemann and Reiter (1992) and Fritzsche (1994).

The car-following models presented in Brackstone and McDonald (1999) are based on the knowledge and input from the time when they were developed. In more recent years many of the aforementioned car-following models have been extended and improved based on new knowledge and more precise vehicle data that have the ability to reflect individual vehicle behavior. Examples of more recent models proposed in the literature to better reflect the complex behavior of drivers are the models proposed by Treiber et al. (2000) and Newell (2002).

Nowadays, vehicle behavioral data is easy accessible through for example roadside detectors, gps-data, driving simulators etc. The level of detail of the collected data is much more precise, and vehicle trajectory data can be obtained due to more powerful computers, and the use of more advanced equipment. Some examples are the studies by Ossen and Hoogendoorn (2011) and Ossen et al. (2006) where vehicle trajectory data have been collected through a helicopter taking pictures of the traffic flow with a digital camera. The frequency of the pictures is high which allow for tracking of individual vehicles in the flow, resulting in individual vehicle trajectory data. Other examples are Ranjitkar et al. (2004) and Punzo and Simonelli (2005) where GPS data, such as speed and location of equipped vehicles have been collected. Kesting and Treiber (2008) uses equipped vehicles
Chapter 3. Microscopic traffic simulation for modeling of ITS

with radar sensors to determine the gap between a vehicle and its predecessor.

By collection and analysis of vehicle trajectory data different driving styles have been obtained, see e.g. Ranjitkar et al. (2004); Punzo and Simonelli (2005); Kesting and Treiber (2008) and Ossen and Hoogendoorn (2011). The studies show that drivers behave differently depending on driver and vehicle type. In Kesting and Treiber (2008) and Punzo and Simonelli (2005) a non-constant driving style is obtained meaning that driving parameters are time dependent. Therefore, different car-following models and different parameter settings are suitable for different vehicle and driver types, as well as for different time periods and road conditions. The results are used to show how well a number of car-following models specified in the studies reflect reality. Especially Kesting and Treiber (2008) and Ossen and Hoogendoorn (2011) indicate the need for new and improved car-following models to better reflect real-world conditions on the road, such as different driving styles under different driving conditions and for different vehicle types and time dependent driving parameters.

One assumption which already early have been questioned in the aforementioned car-following models is the assumption that a driver only take into account one vehicle, i.e. one leader, when deciding on desired speed. In the studies by Kesting and Treiber (2008) and Ossen and Hoogendoorn (2011) the importance of taking into account multi-leader stimuli is highlighted. An extension of the GHR model to include multi-leader stimuli was proposed already by Bexelius (1968). Lately, when calibration through vehicle trajectory data have been available, a number of papers have considered extending some of the proposed car-following models to also incorporating multi-leader stimuli. Examples of such papers are Lenz et al. (1999); Treiber et al. (2005) and Hoogendoorn et al. (2006). In the paper by Hoogendoorn et al. (2006), also a comparison against vehicle trajectory data is performed indicating more realistic car-following modeling by introducing multi-leader stimuli.

The computers have become more and more powerful, allowing for a detailed level of modeling of each vehicle within the simulation. This has led to a development of car-following models in the area of fuzzy logic, such as for example using a rule based neural network approach as proposed in Chong et al. (2013). Here machine learning based on vehicle trajectory data is the basis for the car-following model.

The need for evaluation of ITS have also led to that the car-
3.2. Microscopic traffic simulation tools

Following models have been extended to allow for vehicle behavior related to in-vehicle ITS. In Hoogendoorn et al. (2013), a car-following model have been extended to model driver distraction as a result of performing multiple tasks related to ITS applications. Tang et al. (2014) extend a car-following model to allow for V2V communication during an accident.

In Table 3.1 some of the most common microscopic traffic simulation tools are presented together with a short summary of the origin of the model and the car-following model used. The simulation tools are presented and discussed in more detail by Barceló (2010).

**Table 3.1:** Commonly used microscopic traffic simulation tools together with their origin country of development and the car-following model used.

<table>
<thead>
<tr>
<th>Simulation tool</th>
<th>Country</th>
<th>Car-following model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paramics</td>
<td>UK</td>
<td>Psycho-physical model based on Fritzsche (1994)</td>
</tr>
<tr>
<td>Vissim</td>
<td>Germany (PTV)</td>
<td>Psycho-physical model by Wiedemann and Reiter (1992)</td>
</tr>
<tr>
<td>Aimsun</td>
<td>Spain</td>
<td>Safe distance model based on Gipps (1981)</td>
</tr>
<tr>
<td>MITSIM</td>
<td>U.S.</td>
<td>Stimulus-response model based on the GHR model</td>
</tr>
<tr>
<td>SUMO</td>
<td>Germany</td>
<td>Safe distance model based on Krauß (1998)</td>
</tr>
<tr>
<td>DRACULA</td>
<td>UK</td>
<td>Three different models depending on driver state. Alert and non-alert: Safe distance model based on Gipps (1981) with different reaction time and acceleration depending on state, close following: Newtonian equations of motion, first proposed by Leutzbach and Wiedemann (1986) and calibrated in Brackstone et al. (2002)</td>
</tr>
</tbody>
</table>

Apart from the two fundamental core models used in every microscopic traffic simulation model, each tool has its own modeling lan-
Chapter 3. Microscopic traffic simulation for modeling of ITS

guage, modeling options, and degree of freedom when performing a simulation. Since the modeling of vehicle/driver behavior are done in various ways depending on the car-following model, lane changing model, etc., the vehicles in the simulation will of course behave differently depending on the tool used. Therefore, when making use of microscopic traffic simulation the knowledge of the specific simulation tool is important for the final results. The simulation environment is never going to perfectly reflect reality, but assumptions leading to how well it reflects reality, how results can be interpreted with respect to the underlying models etc., are important for the success of a simulation study.
3.3 SUMO

Simulation of Urban MOBility (SUMO) is a microscopic traffic simulation tool originally developed by the Institute of Transportation Systems at the German Aerospace Center. The main purpose when developing the tool has been, and is, to have a common simulation platform to get comparable results when used among different users, and where it is easy to change and understand the code. SUMO is distributed as open-source code which makes it possible to extend and/or change the underlying models. The development of existing models, as well as implementation of new applications, are a continuously ongoing process mainly within the German Aerospace Center but with much contribution from the users of the tool. The current version of SUMO is multi-modal, space continuous and time discrete. The coding is done in C++. A Traffic Control Interface (TraCI) enables communication between SUMO and an externally developed script making it possible to incorporate new applications in the simulation without changing the core source code. The simulation can be viewed in run time through a Graphical User Interface (GUI) or by evaluating output data gathered as xml-files. XML-descriptions are used for the network building and the demand description, and can either be designed directly in SUMO or imported from for example VISSUM, Vissim, Shapefiles, Open Street Map, etc., and converted to XML-descriptions.

Previous applications

SUMO has been continuously developed since 2000 and several projects, such as the European projects iTETRIS (iTetris, 2010) and DRIVE C2X (DRIVE C2X, 2011), have used SUMO over the years. The open source availability have made it easy to couple SUMO to a network simulator. A network simulator is utilized for modeling and evaluation of different types of protocols used for sending information when applying ITS. Many SUMO users are therefore not mainly traffic researchers, but rather experts on telecommunication but within the ITS field. In Schumacher et al. (2009) an investigation is made of how integration of a network simulator and SUMO could be used to realistically simulate the transmission of information between vehicles, and between vehicles and the infrastructure in urban areas. The coupling of simulators could also be used for evaluation of the
effects the communications between vehicles and vehicles and the infrastructure will have on the road traffic. Two different inter-vehicle communication protocols used for incident warnings in vehicle ad-hoc networks is evaluated in Sommer et al. (2008) by using a network simulator together with SUMO. SUMO has also been frequently used for evaluation of traffic light control systems, see for example Krajzewicz et al. (2005), where an agent based traffic light control algorithm was implemented and evaluated by the use of SUMO. Other systems have also been investigated such as platooning of autonomous vehicles by assuming inter vehicle communication, see e.g. Fernandes and Nunes (2010). The characteristics of the vehicles within a platoon was modeled by changing the car-following model used in SUMO. No network simulation was used since it was assumed that all vehicles in the platoon were able to receive the information sent.

Core models

In SUMO the default car-following model is a space continuous, time discrete model, developed and described by Krauß (1998). The model can be classified as a safe distance model and parallels the underlining approach of the Gipps model (Gipps, 1981), in which braking distances are the main consideration. The idea is that the final speed in which a vehicle travels in is the minimum of: (1) the maximum speed the vehicle can drive in, \( v_{\text{max}} \), and (2) a safe speed, \( v_{\text{safe}} \), which allows the vehicle to drive in a safe way without collisions. The model is taking into account the fact that the acceleration and deceleration has some lower and upper bound, i.e. \((-b \leq \frac{dv}{dt} \leq a, a, b > 0)\). In SUMO the maximum safe speed of a vehicle is described by

\[
v_{\text{safe}}(t) = v_l(t) + \frac{g(t) - g_{\text{des}}(t)}{\tau_{\text{des}}},
\]

where \( v_l \) is the speed of the leading vehicle, \( g(t) \) is the gap between follower and leader, \( g_{\text{des}}(t) = v_l \cdot \tau \) is the follower’s desired gap to the leader, where \( \tau \) is the reaction time of the follower, and \( \tau_{\text{des}} \) is the desired relaxation time calculated as \( \tau_b + \tau \), where \( \tau_b = \bar{v}/b(\bar{v}) \). \( \bar{v} \) is the average speed of the leader and the follower, and \( b(\bar{v}) \) is the desired deceleration function. The deceleration function is approximated by \( b(\bar{v}) = b \), assuming that the leader and the follower has the same maximum deceleration abilities, \( b \).
The desired speed for each individual vehicle at each time step $t$, $v_{\text{des}}(t)$, is taken as the minimum of the maximum speed of the vehicle $v_{\text{max}}$, the speed using the vehicle’s maximum acceleration ability $a(v)$, and the safe speed, i.e.

$$v_{\text{des}}(t) = \min (v_{\text{max}}, v(t) + a(v)\Delta t, v_{\text{safe}}(t)),$$ (3.3)

where $\Delta t$ is the simulation time step.

A difference compared to the original Gipps-model is the assumption that the driver is not perfect in holding its desired speed (Ranjitkar et al., 2005). This driver imperfection is modeled as a stochastic deceleration, as the drivers are assumed to drive with a final speed that is somewhat lower than the desired speed. The final speed for the individual vehicles is given by

$$v(t + \Delta t) = \max (0, v_{\text{des}}(t) - r \cdot a(v) \cdot \epsilon),$$ (3.4)

where $r$ is uniformly distributed with values between 0 and 1, $\epsilon$ is an input parameter ranging between 0 and 1 depending on the degree of imperfection.

Some further extension has been made to the original Gipps-model:

- The ability of acceleration is decreasing with increasing speed (modeled using a linear function).
- The driver’s imperfection is reduced when accelerating from low velocities (two cases is considered depending on the vehicle’s speed).

The car-following model is described and discussed in detail in Krauß (1998) and Krajzewicz (2010).

The other core model included in a microscopic traffic simulation model is the lane-changing model. The lane-changing model has been continuously developed since the first version of SUMO. The current model takes into account the drivers’ route and lane-changing requirements in order to be able to continue on the selected route to the vehicle’s given destination.

First, the assumed distance needed for vehicle $i$ to be able to change lane at time $t$ is calculated. The assumed distance needed is based on the speed in which a vehicle is driving, and calculated as

$$d_i(t) = v_i(t) \cdot \alpha + 2 \cdot l_i,$$ (3.5)
where $v_i(t)$ is the speed of vehicle $i$ at time $t$, $\alpha$ is a scaling factor currently set to 15 and 5 seconds, respectively. If the speed of vehicle $i$ is above 14 m/s a longer assumed distance is needed in order to change lane and if the speed of vehicle $i$ is below 14 m/s a shorter assumed distance is needed in order to change lane.

The benefit of changing to a neighboring lane $l_n$ at time $t$ is calculated based on the safe speed in the current lane and the safe speed in the lane considered as a possible lane change opportunity,

$$b_{l_n}(t) = \frac{v_{\text{poss}}(t, l_n) - v_{\text{poss}}(t, l_c)}{v_{\text{max}}(l_c)},$$

(3.6)

where $l_c$ is the current lane, $v_{\text{poss}}(t, l)$ is the safe velocity for the vehicle located in lane $l$ at time $t$ and $v_{\text{max}}(l)$ is the maximum velocity, under free flow conditions in lane $l$. A memory variable is used to model the driver's desire to change lane. If the calculated benefit of changing lane for a specific vehicle $i$ at time $t$ is greater than 0 it means that the desire to change lane is increasing. In this case the calculated benefit of changing lanes is added to the current value of the memory variable. If the calculated benefit of changing lane for a specific vehicle $i$ at time $t$ is smaller than 0 the desire to change lane is decreased. In this case the current value of the memory variable is divided by 2.

The vehicle is changing lane if the absolute value of the memory variable reaches over a certain threshold. The sign of the memory variable specifies the direction to where the vehicle should change lane. If the vehicle has no option to change lane due to the desired lane it starts to interact with the vehicles in the front and the back. The vehicle starts to accelerate or decelerate depending on the situation according to,

$$v_{\text{next}}(t) = \begin{cases} v_{\text{decel}}(t), & \text{if blocking/blocked at own back and front;} \\ v_{\text{decel}}(t), & \text{if blocking/blocked at own front;} \\ v_{\text{accel}}(t), & \text{if blocking/blocked at own back;} \end{cases}$$

where $v_{\text{next}}(t)$ is the speed after adaptation to vehicles in from and in back of the vehicle under consideration, $v_{\text{decel}}(t)$ is the speed of the vehicle after decelerating, $v_{\text{accel}}(t)$ is the speed of the vehicle after accelerating. The acceleration and deceleration speed is calculated according to,
3.4. Estimating emissions in microscopic traffic simulation

\[ v_{\text{accel}}(t) = v_{cf}(t) + \frac{v_{\text{max}}(t)}{2} \]  
\[ v_{\text{decel}}(t) = v_{cf}(t) + \frac{v_{\text{min}}(t)}{2} \]

where \( v_{cf}(t) \) is the speed at time \( t \) given by the car-following model (including imperfection), \( v_{\text{max}}(t) \) is the speed at time \( t \) after maximum possible acceleration (in accordance with the car-following model), \( v_{\text{min}}(t) \) is the speed at time \( t \) after maximum possible deceleration (in accordance with the car-following model).

One problem with this model according to Krajzewicz (2010) is that when the vehicle is approaching a queue that is standing still and the lane must be used to continuing the route, but there is a possibility to change lane and pass the queue before continuing the route, the vehicle does not change into another lane in order to pass the queue.

The lane-changing model in SUMO is continuously updated and the model described here is based on the description presented in Krajzewicz (2010).

3.4 Estimating emissions in microscopic traffic simulation

Assessment of the environmental impacts of road transport requires quantification of vehicle pollutant, greenhouse gas emissions and fuel consumption. The current vehicle emission models can generally be classified into aggregate and microscopic models. Aggregate models, such as ARTEMIS/HEBEFA (Keller and Kljun, 2007), MOBILE6 (Vallamsundar and Lin, 2011; EPA, 2003) and COPERT4 (EEA, 2013) are based on the trip average speed and a set of traffic situations to predict emission levels. They are intended for emission inventory of large road networks, or for evaluation of the impacts of infrastructure projects, where macroscopic or mesoscopic traffic models are used to estimate average speeds. Aggregate emission models are therefore not sensitive to variations in vehicular instantaneous speed and acceleration, which can have a major effect on the emissions and fuel consumption according to Panis et al. (2006).

To evaluate the environmental impacts of real-time ITS applications on a micro-scale, for example in a congested highway section or
an urban street or at road junctions, where vehicle operating modes are queuing, accelerating and decelerating rather than steady cruising, microscopic emission models are more suitable. Micro-scale emission models predict emission rates based on the instantaneous speed profiles and vehicle operating factors, such as the engine parameters. The models can be classified into modal-based and statistical-based approaches. Modal micro-scale models, e.g. CMEM (Barth et al., 2000) and MOVES (Vallamsundar and Lin, 2011; EPA, 2010), consider the modal operation of the vehicle, i.e. idle, steady-state cruise and various levels of acceleration, and are based on detailed physical analysis of the emission production process to predict instantaneous emissions as a function of the driving modes. One example is the Comprehensive Modal Emission Model (CMEM), where the emission levels are estimated using chassis dynamometer data (Scora and Barth, 2006). The model calculates second-by-second tailpipe emissions as a product of three parameters

\[ e_{\text{tailpipe}} = r_{\text{fuel}} \cdot i_{\text{em/fuel}} \cdot C_{\text{pass}}, \]  

(3.9)

where \( r_{\text{fuel}} \) is the fuel rate, \( i_{\text{em/fuel}} \) is the engine-out emission index and \( C_{\text{pass}} \) is the catalyst pass fraction. The output emissions given by CMEM are HC, NO\(_x\), CO, CO\(_2\) and fuel consumption.

Statistical micro-scale models, e.g. Lei et al. (2010), predict instantaneous emission rates through regression models including speed, acceleration, their product and dummy variables for the driving modes. The regression estimate the best set of regression parameters used for prediction of the emission rates.

When evaluating ‘traditional’ ITS and cooperative systems used for motorway traffic management applications, potential benefits, such as flow harmonization and decreased emission rates, are expected. The emissions will be highly dependent on the acceleration rates of the vehicles in the traffic flow, and will therefore require a micro-scale emission model. Integrating the micro-scale emission model CMEM with a microscopic traffic simulation model for estimation of emission rates has been proven useful in several studies, see e.g. Yelchuru et al. (2011), Noland and Quddus (2006) and Chen and Yu (2007). CMEM is therefore deemed suitable for estimation of exhaust emissions based on the resulting vehicle trajectories from a microscopic traffic simulation tool such as SUMO.
Chapter 4

Variable speed limit systems

One commonly used motorway control strategy with the aim to increase safety and efficiency on the road is to use series of signs displaying variable speed limits to the passing vehicles. These systems are often referred to as Variable Speed Limit (VSL) systems.

Evaluations of already existing VSL systems have been performed as field-tests and by the use of traffic simulation. Traffic simulation studies have also been carried out on proposed improved and new versions of VSL systems. The results from the evaluations of the systems indicate benefits in terms of safety and traffic efficiency.

In this chapter, an introduction to VSL systems are given in Section 4.1. Section 4.2 gives examples of the already implemented VSL systems. Control algorithms used in VSL systems are discussed in Section 4.3. In Section 4.4 field studies of implemented VSL systems are presented. Traffic simulation studies evaluating VSL systems are presented in Section 4.5.

4.1 Introduction to variable speed limit systems

Standalone VSLs are often used for lowering the speed at one specific location. Examples of such location could be at dangerous locations,
such as at road works, at intersections, on roads with limited visibility and during certain hours, etc. They are also used at road sections where specific weather conditions might lead to dangerous situations. An example is road sections at bridges where there is a high risk for under-cooling at temperatures around the freezing point.

VSLs could also be used for lowering the speed when the traffic flow is high and when incidents/accidents are more probable to occur. The main objective for lowering the speed in high traffic volumes has been for safety reasons. Additionally, the cost of delays are becoming high for society with increasing traffic flows leading to congestion. Therefore, VSLs have also been introduced in order to harmonize the flows and thereby increase efficiency.

Usually congestion appear at peak-hours, and propagate over a longer road stretch. One standalone VSL is therefore not enough to give a desirable effect. The use of many VSL that are linked together via a control algorithm has resulted in so called VSL systems. The algorithm is used for deciding on the speed limits to be displayed at the VSL signs based on the conditions close by the VSL sign, but also on the conditions at VSLs further upstream and downstream. The conditions on the road are collected through detectors, where the most common measurements to use are local speed or flow. The calculated speed limits are displayed at VSL signs in connection to the detectors. The displayed speed limits can be either compulsory or recommended. A VSL system can be used solely for lowering the speed based on detector values, or it can be included in a Motorway Control System (MCS). An MCS has the purpose to control the traffic flows not only by lowering the speed limits but also by closing lanes and restricting lanes to certain vehicle types, etc.

The two most common approaches when implementing a VSL system is to use it as an incident detection system, or for homogenization of the traffic flows.

The incident detection systems, sometimes also referred to as warning systems, have as main objective to detect situations where incidents/accidents are more probable to occur. This means that the system is triggered when a breakdown, i.e. very low speed situations, in the traffic system has occurred. The purpose with the change in speed limits is to limit the risk of further breakdown and to try to resolve congestion.

The homogenization systems have another approach. The main objective is to keep the traffic flows homogenous at all times. Mean-
4.2 Example of existing variable speed limit systems

The purpose of these systems is to prevent a breakdown by taking early action. This can be done by prediction of the future traffic states, or by using current and historic information about the traffic conditions on the road to evaluate the risk of a breakdown.

Many of the systems implemented today have algorithms for deciding on suitable variable speed limits to be displayed that are based on simplistic rules. Predefined thresholds are used for deciding when the speed should be decreased and increased, respectively. The average speed and/or the average flow at each detector station are compared to the predefined thresholds and the speed limit displayed at the VSL is changed if needed. The speed limit displayed at the VLS is often determined based on local regulations set up by authorities and is usually lowered substantially from the original speed limit on the road. The coupling between VSLs are usually only used for preventing abrupt speed changes, i.e. when the variable speed limit is lowered at one VSL, the VSLs further upstream are used to gradually decrease the speed of the vehicles towards the new speed limit. As a result of the simplistic rules and the big difference between the displayed speed limit and the original speed limit on the road, the conditions on the road when the variable speed limits are activated are likely to already be at a congested state. In this case the variable speed limit is not reflecting the actual flow on the road, and becomes more of an indicator to the driver of congestion/incidents further downstream, i.e. an incident detection based system.

4.2 Example of existing variable speed limit systems

Two example of systems currently implemented in Europe are presented in the sections below.
Motorway control system, Sweden and the Netherlands

An example of a VSL system, is the system included in the Netherlands MCS (van den Hoogen and Smulders, 1994). A similar system has also been implemented in Stockholm, Sweden (van Toorenburg and de Kok, 1999). The main objective with the VSL algorithm, called automatic incident detection, is to detect incidents and to have a successive decrease of speed when approaching the incident. The definition of an incident is based on the mean speed, i.e. when the mean speed is below a predefined threshold an incident is assumed to have occurred.

The system implemented in Stockholm is displaying recommended variable speed limits, i.e. it is not mandatory to obey the speed limits. In the Netherlands both mandatory and recommended variable speed limits exists. A red circle around the posted speed limits correspond to a mandatory variable speed limit. The Netherlands have implemented photo radars to keep a high level of compliance with the mandatory speed limits.

The automatic incident detection algorithm can be summarized in the steps below. The values of the Stockholm system on a road with 90 km/h as original speed limit has been taken as example to make it easier to understand the description.

- If the VSL signs are inactive:
  - The mean speed at each detector of the road section equipped with the system are collected.
  - The mean speed at each detector is compared to a predefined threshold for lowering the speed, $v_{\text{low}}$, in this case 35 km/h.
  - If the mean speed at a detector is below $v_{\text{low}}$ the system becomes activated and the displayed speed limit at that detector location is lowered to a predefined value, in this case 50 km/h.
  - The displayed speed limits upstream of this detector are also lowered with a lead-in speed limit to avoid abrupt changes in speed going from one road segment to another. The number of affected VSLs are dependent on how much the displayed speed limit at the detection point is lowered compared to the original speed limit on the road section.
4.2. Example of existing variable speed limit systems

The lead-in speed limit in the Stockholm case is 70 km/h and only one VSL upstream is affected.

- If the VSL signs are active:
  - The mean speed at each detector of the road section equipped with the system are collected.
  - Lowering of the speed limits is functioning in the same way as when the VSL signs are inactive.
  - A predefined threshold, $v_{\text{high}}$, in this case 50 km/h, is used for increasing the displayed speed limits at each detector.
  - If the mean speed at a detector is above $v_{\text{high}}$ and the displayed speed limit has previously been lowered, the displayed speed limit at that location is increased to the original speed limit on the road, which in this case is 90 km/h.
  - Also the VSL signs upstream of that detector, displaying lead-in speed limits, are updated to the original speed limit on the road.

The predefined value for the lowered variable speed limit as well as the threshold are depending on the original speed limit on the road, and the legislation of the specific country.

The variable speed limits could be set differently for different lane or the same value could be used for all lanes. If the same value is used for all lanes the most restrictive lane is regulating the speed limit, i.e. the lane with the lowest mean speed is considered when determining the speed limit for all lanes.

A harmonization algorithm could also be included in the MCS, trying to keep the flow stable at high traffic flow conditions. In case of harmonization the speed reduction would not be as high as in the case of incident detection. In the VSL system which is part of the Stockholm MCS in Sweden this has not been included this far. Experiments with inclusion of a harmonization algorithm have been performed in the Netherlands, see section 4.4. But no actual implementation of the algorithm have been done (Middleham, 2006).

**M25, controlled motorway, UK**

M25 is a controlled motorway in London (Highway Agency, 2006). The system consists of a VSL system together with variable message signs showing warnings in text, such as for example 'road work ahead'. The controlled motorway have two main objectives. One objective is
to reduce speed in order to avoid congestion and the other objective is to reduce speed in order warn drivers and create a safer driving environment when incidents occur. The system implemented on M25 is mandatory, i.e. it is compulsory to obey the speed limits shown on the VSL signs. The original speed limit on the road is 70 mph (112 km/h).

The algorithm can be summarized in the following steps:

- **Reduction of speed due to congestion:**
  - The mean flow at each detector is collected.
  - The mean flow is compared to two predefined thresholds, $q_1$ and $q_2$.
  - If the mean flow at a detector is above $q_1$, the displayed speed limit is lowered to 60 mph (96.6 km/h).
  - If the mean flow is even further increased to above $q_2$, the displayed speed limit is lowered to 50 mph (80.5 km/h).
  - If the mean flow decreases to between $q_1$ and $q_2$, the displayed speed limit is increased to 60 mph (96.6 km/h).
  - If the mean flow decreases below $q_1$ the original speed limit on the road is displayed on the VSL sign.

- **Reduction of speed due to incident**
  - The mean speed at each detector is collected.
  - The mean speed is compared to a predefined threshold, $v_{low}$. The threshold is used for identifying incidents at detectors, i.e. slow moving traffic or stationary traffic.
  - If the mean speed at one detector is below the threshold $v_{low}$, the displayed speed limit is set to 40 mph (64.4 km/h).
  - The displayed VSL upstream of the detector location is set to 60 mph (96.6 km/h) to avoid abrupt changes in speed going from one road segment to another. Exceptions exist when two VSL signs are close to each other. In this case the displayed speed limit at the upstream location is set to 50 mph (80.5 km/h).

To ensure compliance with the speed limits displayed on M25 a speed enforcement system is used. The speed enforcement system consists of speed cameras operating at all lanes.
4.3 Control algorithms for variable speed limit systems

The design of the VSL control algorithm is dependent on the defined objective of the system and this will in turn have an affect on the resulting outcome. Usually the objective with the algorithm is related to increasing safety or efficiency. Lately, the objective of decreasing environmental impacts have been included in algorithms presented in the literature as a result of the increasing interests with respect to environmental issues. The objective can also be a combination of two or more of the above mentioned issues. The objective might sometimes even be contradictory. For example if safety is the main objective, the VSL signs are more probable to display lower speed, resulting in longer travel times and maybe also higher emissions. If efficiency is the main objective with the algorithm, safety might decrease. And finally, if emission levels is the main objective, the VSL signs might display lower speeds due the fact that vehicles often performs at their best, considering emission levels, at around 70 km/h (Den Tonkelaar, 1991). But on the other hand many studies have concluded that harmonization lead to better traffic situations, see e.g. Highway Agency (2007); Smulders and Helleman (1998); Carlson et al. (2011); Lee et al. (2006), and this will most probably affect both travel times, emission levels, and safety in a positive manner.

In the previous section, two VSL systems implemented in Europe where presented. Most of the algorithms that are implemented in systems that exists today are based on simplistic rules such as lowering the speed based on thresholds for mean speed or mean flow or a combination of the two. Various algorithms have been proposed in the literature making use of both current information and historic information in order to decide on new speed limits to be displayed on VSL signs, see e.g. Lee et al. (2006); Hegyi et al. (2005); Hegyi et al. (2008); Zegeye et al. (2011) and Carlson et al. (2011).

The algorithms proposed in the literature can be categorized into predictive algorithms and reactive algorithms. Predictive algorithms are often related to model predictive control (Morari and Lee, 1999; García et al., 1989). In model predictive control the future traffic states are predicted based on a dynamic model of the process, i.e. the traffic flow evolution, a history of past control actions and an optimization cost function. The optimization process, with the aim
Chapter 4. Variable speed limit systems

of minimizing the cost function, results in a final speed limit to be displayed on the VSL signs. The design of the cost function is dependent on the aim and the purpose of the VSL system. Examples of algorithms based on model predictive control presented in the literature are Hegyi et al. (2005) and Zegeye et al. (2011). Hegyi et al. (2005) have applied a cost function based on total time spent, i.e. the total number of vehicle hours spent on the considered road stretch, for calculation of the speed limits. Whereas Zegeye et al. (2011) have applied a cost function taking into account one or more of the following: total time spent, total emission levels and maximum dispersion of emission levels, for calculation of the speed limits. Both algorithms perform well with respect to their aim.

The reactive algorithms calculate the speed limits to be displayed on VSL signs without applying a model for prediction of the future states. The calculations made are only based on measured data collected from loop detectors, and threshold values. Reactive models can also in some sense predict the future evaluation of the traffic. One such example is a PID controller (proportional-integral-derivative controller), which is a three-term controller, trying to control the error between a measured value and a predefined threshold value. The derivative term of the controller is related to the prediction of the future errors, but only based on the current state which can be collected from detector data. Examples of reactive algorithms presented in the literature are Lee et al. (2006); Hegyi et al. (2008) and Carlson et al. (2011).

According to Hegyi et al. (2008), many of the algorithms proposed in the literature often require a considerable amount of data, are computationally complex, have uncertainty in robustness and/or tuning difficulties of parameters. The tuning difficulties are often a result of too many parameters to tune or interpretation issues of the parameters.

Under real-world conditions a fast algorithm showing the speed limits immediately, or almost immediately, after the measurements have been collected is desirable. The calculations have to be fast in execution time, and the parameters and the design of the algorithm should be easy to interpret. This is often not the case in predictive models, which are usually computationally intense compared to the reactive models.
4.4 Studies on the performance of existing variable speed limit systems

VSL systems with various functionalities depending on the purpose of the system, the application site, etc. have already been implemented in many countries. Examples of implemented VSL systems include the before mentioned systems in the UK (Highway Agency, 2007) and the Netherlands (van den Hoogen and Smulders, 1994). Studies of these systems have been carried out to evaluate how the implementation of the systems will affect the traffic flow.

In the UK a comprehensive study of the system performance have been carried out by Highway Agency (2007). The study has been conducted by monitoring traffic data before and after the system was implemented. Two years before and one year after the systems was implemented has been included. The traffic data was gathered from loop detectors, from instrumented vehicles and from automatic number plate recognition data. Environmental data was collected during a six month period before and after the system was installed. The environmental data included noise surveys and exhaust emissions calculated based on typical driving profiles from the instrumented vehicles and vehicle emission values from a database. Finally, accident data was gathered from different databases over a two and a half years period.

The evaluation has covered a number of areas, where the main benefits are smoother and more reliable journeys in certain periods, reduction in stress for drivers, reduction in the number of severe accidents, reduction in traffic noise, vehicle emissions and fuel consumption, and improved driver behavior.

Even though the journey times have been improved with respect to smoothness and reliability there is no reduction in journey time. This means that the difference in journey time between lanes are more equal, but for some drivers, usually drivers on the fast lane, the journey time will actually increase. Also throughput have been investigated, showing that in the peak-hour the system can not manage to increase the throughput. If a longer period is considered as peak-period the throughput is slightly decreased. This indicates that the system is not efficient with respect to throughput for very high traffic flows. The number of injury accidents during the measurement periods was reduced by 15%. The exhaust emission levels are
dependent on the type of emission but ranges between 2% and 8%.
Since the system make use of mandatory displayed speed limits and
speed cameras, the compliance level was high. Finally, more uniform
headways, decreased speed differential between lanes, decreased stop-
and-go traffic during peak-hours, as well as a decrease in duration
and number of breakdowns, indicate a more harmonized traffic flow.

The Swedish MCS, based on the system implemented in the Nether-
lands, have been evaluated by Nissan and Bang (2006) and Nissan and
Koutsopoulos (2011). The 2006 study was set-up as a before-and-
after study. The data included both loop detector data, video data
and data from an instrumented vehicle collected during one month be-
fore installation and one month after installation of the system. The
traffic characteristics analyzed was traffic flow distribution and com-
position, mean headway and the distribution of headways, spot speed
and speed distribution, travel time and delay, and lane change fre-
quency. The results showed that the main impact was harmonization
in speed due to a decrease in variation of speeds among the vehicles.
Also the number of lane changes between the middle and the left lane
was reduced. However, the study performed by Nissan and Kout-
sockopoulos (2011) concludes that there are no statistically significant
impacts comparing the results from the before-and-after study. The
study includes both immediate impacts, right after implementation
of the system, and long term impacts, several month after implemen-
tation of the system. The reason for this might, according to the
authors, be that the system implemented in Stockholm is not manda-
tory, and as a result of that the compliance level is very low. This
might in some cases even increase the deviation in speed. The results
are in line with the study by Berg and Bukkems (2001) comparing the
Swedish and the Netherlands MCS. It is concluded that the main dif-
ference between the systems are that the speed limits are mandatory
in the Netherlands and not in Sweden. This is according to the study
resulting in enhanced safety in the Netherlands by 20% fewer acci-
dents compared to Sweden where only harmonized and lower speed
levels were detected. The road capacity was slightly increased in the
Netherlands and the journey times was reduced by 10-15%, compared
to Sweden where no such effects where observed. On the other hand,
a reduction of emission impacts was detected in Sweden.

A comparison study on systems implemented in Germany, the
Netherlands and the UK has been performed by Smulders and Helle-
man (1998). The main objective for implementing the systems, irre-
4.4. Studies on the performance of existing variable speed limit systems

spectively of country, have been to increase safety. Both the UK and the Netherlands have been focusing on congestion reduction as part of the system. The literature study show that the results for Germany and the Netherlands are in line with the above findings for the system implemented in the UK, with harmonized flows as one of the most highlighted benefit. No significant improvements could be concluded on congestion, throughput and capacity in the study. The number of accidents for the compared systems is another important indicator of the system performance, especially since the main target for all of the systems are safety aspects. All systems indicate a large decrease in number of accidents, 20-30% according to Smulders and Helleman (1998). Although, the conclusions are based on limited accident data and consequently the results can not be statistically proven.

Apart from the field studies of existing VSL systems, van den Hoogen and Smulders (1994) carried out an experiment on the MCS in the Netherlands. A homogenization algorithm was introduced and applied in dense traffic. The speed limit was lowered from 120 km/h to 90 or 70 km/h on the test site. The purpose with the homogenization algorithm was not to lower the speed but rather to stabilize the flow by decreasing deviation in speed between lanes. The results showed that the traffic flow became more homogenous with respect to speed distribution. The mean speed and the throughput decreased by a small amount, i.e. the traffic efficiency was not increased. The homogenization algorithm was applied on a road stretch including a bottleneck. But no positive effect was noticed with respect to solving congestion at this bottleneck.

As a summary, the M25 controlled highway indicates benefits with respect to flow harmonization, emission levels, and safety. Similarly, the comparison study including Germany, the Netherlands and the UK indicate benefits in terms of increased harmonization and safety effects. Both the study performed in the UK and the comparison study shows no improvements in throughput, capacity and congestion. Also, the Swedish system indicate an increase in terms of flow harmonization, although the results are not statistically significant. The limited improvements can according to the author possibly be explained by the fact that the displayed speed limits are only being recommended. This indicates the importance to use mandatory displayed speed limits to get a desirable effect. The experiment performed by van den Hoogen and Smulders (1994) indicate that the integration of a homogenization algorithm have positive effects on
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the speed distribution among lanes, leading to a more stable traffic flow pattern.

4.5 Simulation based studies of variable speed limit systems

Besides field tests, one direct way to study VSL systems is by the use of traffic simulation. Traffic simulation may lead to a less costly evaluation of existing systems, but more importantly, it will be possible to evaluate systems that are not yet implemented. Numerous studies have been conducted on VSLs and VSL systems using traffic simulation, resulting in good indications on the general system performance. Most of the simulation studies have been focusing on safety, see e.g. Abdel-Aty et al. (2006); Allaby et al. (2007); Lee et al. (2006); Hellinga and Mandelzys (2011) and Piao and McDonald (2008) and efficiency, see e.g. Zhicai et al. (2004); Torday et al. (2011); Carlson et al. (2011); Carlson et al. (2013); Hegyi et al. (2005) and Hegyi et al. (2008). However, few simulation-based evaluations of VSL systems considering environmental impacts have been found in the literature, exceptions include Torday et al. (2011) and Zegeye et al. (2011).

Many of the studies presented are based on microscopic traffic simulation. But also macroscopic traffic simulation have been considered in Papageorgiou et al. (2008); Hegyi et al. (2005); Hegyi et al. (2008) and Zegeye et al. (2011).

Identification of safety benefits related to VSL systems could be done in many ways. One way is to measure the standard deviation of speed in lanes and between lanes, and the acceleration levels or stop-and-go traffic. One alternative method for evaluating safety benefits is proposed in Lee et al. (2003), considering a so called crash potential. The crash potential is based on crash precursors, such as temporal variation of speed, the spatial variation of speed, lane change behavior, and external factors, such as weather conditions, road geometry and peak or off-peak situations. The crash precursors are determined based on linear regression analysis of existing data of a motorway section in Toronto, Canada. According to Lee et al. (2003), the method can be used for prediction of risky situations. Thereby, a VSL system could be applied with the objective to lower the speed limits when the crash potential is high.

In Lee et al. (2004) and Lee et al. (2006) the method of using crash
4.5. Simulation based studies of variable speed limit systems

Potential for deciding on speed limits in VSL systems have been investigated. The idea is to lower the speed limit if the crash potential is high in order to reduce the variance in speed. Microscopic traffic simulation is used for evaluation of different control strategies. Lee et al. (2004) concludes that VSLs can be used for lowering the crash potential. Although, to result in great safety benefits the threshold for crash potential has to be low, leading to an increase in travel time. The reason for this is frequent intervention of the VSL system leading to repetitively lower speed limits on the road. Also time of intervention of the VSL system has been investigated showing that a too low intervention time might increase the risk of an accident/incident due to frequent changes of the speed limits on the road. Lee et al. (2006) includes an investigation on how the displayed speed limits is determined. The importance of applying a speed limit that is reflecting the actual speed on the road is highlighted. By lowering the speed at a controlled section the crash potential upstream and downstream of this area could actually decrease due to spatial variation of speed. Additionally, the study shows that a threshold exists where both travel time and crash potential can be lowered at the same time.

Samimi and Hellinga (2012) have evaluated how sensitive the control strategy, defined in Lee et al. (2004) and Lee et al. (2006), is to a set of parameters calibrated using a near optimal approach. The near optimal set of parameters are calculated using an automated process to find the optimal parameters by considering a large number of categorizations of the possible set of parameters. It is concluded that the control strategy is not sensitive to the optimal set of calibrated data, with respect to safety benefits. This indicate that the model calibrated for one motorway section could actually be applied to another motorway section and still give similar results.

Abdel-Aty et al. (2006) investigate different control strategies for activation of the VSLs. A microscopic traffic simulator have been used to evaluate the control strategies. The different strategies consider the number of VSLs to display lower speed limits, and both upstream and downstream locations have been considered. Also, the time of intervention have been considered and the distance in space between two speed limit changes, i.e. how many VSLs that should display the same speed limit. A final set of values for the considered parameters have been proposed. The study concludes the VSLs are not effective under highly congested situations.

Allaby et al. (2007) have investigated different control strategies
by taking into account occupancy, average speed and volume for deciding on new speed limits to be displayed on the VSLs. The decision algorithm is based on a decision tree leading to a reduction in speed to 60, 80 or 100 km/h depending on the measurements from the detectors and the threshold used for each category. Microscopic traffic simulation is used for evaluating the different control strategies. The study concludes that travel time is increased independently of control strategy. The safety benefits are increasing for high and moderate flows but for low flows the safety benefits are actually decreasing.

The effects of driver compliance have been investigated by Hellinga and Mandelzys (2011) using microscopic traffic simulation. The same control strategy as in Allaby et al. (2007) have been used. It was concluded that safety is positively correlated with compliance whereas travel time is negatively correlated with compliance. Also, the level of compliance affect the optimal VSL strategy, meaning that the choice of strategy is dependent on the level of compliance.

Zhicai et al. (2004) have divided the control strategies into two categories, one demand driven congestion strategy as a result of high traffic flows and one supply driven congestion strategy as a result of incidents, roadworks, etc. A microscopic traffic simulator have been used to evaluate the two strategies. The results indicate harmonized flows and decreased travel time in case of a demand driven congestion and reduced queue length and travel times in case of a supply driven congestion. The effects seems to be limited under very high traffic volume conditions.

Torday et al. (2011) have performed an evaluation of an existing VSL system located in Barcelona. A microscopic traffic simulator is used for the evaluation. Torday et al. (2011) conclude that the benefits from the systems are largely dependent on the traffic volume. During high volume conditions, the systems tend to have more positive impacts on travel time. However, the benefits in travel time of the VSL system are negligible under normal conditions. This contradicts the previous findings in Zhicai et al. (2004) and Abdel-Aty et al. (2006). Safety benefits such as a decrease of the number of stops and amount of time a vehicles have stopped could be concluded, as well as reductions in air pollutions.

In Carlson et al. (2011) a VSL control strategy based on control theory is applied, called mainstream traffic flow control. The idea is to keep the traffic flow close to capacity to avoid a capacity drop that are otherwise probable to appear in congested situations. The traffic
flow just downstream of a beforehand known bottleneck is controlled by changing the speed limit and thereby also the inflow of the bottleneck. The density, or occupancy level are measured and compared to a predefined threshold. A macroscopic traffic simulation approach have been used for evaluation of the VSL strategy. A few different control scenarios are investigated, such as discrete vs. non-discrete speed limits, lead-in speed limits, etc. The results from the simulations indicate that the total time spent is decreasing when applying a VSL strategy based on control theory, i.e. the traffic efficiency is increased. The results are positive irrespectively of control scenario. Apart from the controller applied in Carlson et al. (2011), two simpler controllers were presented and evaluated in Carlson et al. (2013). Total time spent was reduced in the same range for all the controllers. A microscopic traffic simulation study, presented in Müller et al. (2013), have been applied to a control strategy based on the theory in Carlson et al. (2011). The results indicates large improvements in total time spent, around 30-40%. It should be mentioned that the capacity drop is assumed to be at around 17%. With lower assumed capacity drops the benefits in total travel time would be lower.

Hegyi et al. (2008) introduce a VSL control strategy based on shockwave theory, called SPEed ControllIng ALgorIthm using Shockwave Theory (SPECIALIST). The idea is to detect shockwaves by using detectors on the road. The algorithm uses shockwave theory and linear relationships to predict the propagation of the detected shockwaves. By applying appropriate speed limits the shockwave can possibly be resolved. The control strategy have been evaluated by the use of macroscopic traffic simulation. A shockwave was modeled and the algorithm was applied, giving a decrease in total time spent and increased avarge flow output. The algorithm have also been applied in a field study by Hegyi and Hoogendoorn (2010). The results showed that around 80% of the theoretically resolvable shockwaves were resolved with a gain in total time spent. However, this is based on the assumption that the congestion would have lasted for one hour without applying the VSL control strategy, as a result from previous studies. This means that the base case was not investigated during this field study.

Another type of VSL control strategy, commonly seen in the literature, are the so called model predictive control. The idea is to predict future traffic states and based on that find an optimal control signal, in this case the speed limit, by the use of minimizing a cost
Chapter 4. Variable speed limit systems

function. One example of this is Hegyi et al. (2005), where the purpose was to minimize the total time spent and at the same time have safety constraints, by limiting high speed limit drops. The control strategy was evaluated by the use of macroscopic traffic simulation, showing improvements in total time spent in the traffic system as a result.

Another example is Zegeye et al. (2011), where the cost function is based on total time spent, total emission levels and maximum dispersion of emission levels. The control strategy have been evaluated by the use of macroscopic traffic simulation. Different weights for the different parts of the cost function have been considered. The results are depending on the weights, where the part with highest weights gain the most from the control strategy. A set of weights where all three parts of the cost function are included, and reduced, have been found in the study.

In Lu et al. (2011); Carlson et al. (2012) and Zhang et al. (2006) a VSL system together with a ramp metering strategy has been proposed and investigated.

Lu et al. (2011) uses a similar approach as Carlson et al. (2011), where the aim is to maximize throughput at a bottleneck location by keeping density close to capacity with an I-type regulator. The VSL system is combined with a ramp metering strategy. For the ramp metering strategy model predictive control is used with a cost function including total time spent and total travel distance. A microscopic traffic simulator is used for applying the control strategy and a macroscopic traffic model is used for the VSL system and ramp metering design. According to the author, the traffic performance is increased, considering to total time spent and total travel distance, by introducing ramp metering together with a VSL system.

Also Zhang et al. (2006) uses a combined approach with ramp metering and a VSL system. The control strategy is based on the fundamental flow-density relationship. If the density is above capacity level the VSL signs becomes active and the speed limit used is based on the fundamental flow-density relationship calibrated from real data. It is concluded that by combining the VSL system and a ramp metering strategy the improvements in total time spent are substantial, compared to when only ramp metering is used or in the case of no control.

Carlson et al. (2012) have incorporated a ramp metering strategy to the proposed VSL system in Carlson et al. (2011). The VSL
system is activated when the ramp metering control is about to be exhausted. The VSL system allows for further improvements compared to when only ramp metering is applied. The results indicate that by integrating ramp metering with a VSL system the total time spent can be further decreased.

The above presented simulation studies have different aims and purposes, but with similar effects as conclusions.

Many of the studies show that the design of the VSL control strategies has to be based on a trade-off between safety and travel time, see e.g. Allaby et al. (2007); Abdel-Aty et al. (2006); Lee et al. (2006); Lee et al. (2004). Also a trade-off between emission levels and travel time is seen in Zegeye et al. (2011).

Zhicai et al. (2004) and Abdel-Aty et al. (2006) show that for high traffic volumes the VSL system does not have any effect on traffic efficiency. On the other hand, the opposite have been shown in Torday et al. (2011). Also, a decrease in safety benefits for low flows has been discussed in Allaby et al. (2007). Finally, Hellings and Mandelzys (2011) show that the compliance level affect the success of the control strategy. Careful consideration has to be taken when applying and designing a VSL control strategy in order to not get undesirable effects.

Many of the studies are based on existing or improved control strategies, where lowering the speed is based on threshold values. Some exceptions are Lee et al. (2006); Hegyi et al. (2005); Hegyi et al. (2008); Zegeye et al. (2011) and Carlson et al. (2011) where new methods for deciding on suitable VSL are proposed.

In the studies considered in this section emission levels have only been presented in Torday et al. (2011). One reason for this can be that environmental impacts are a relatively new interest area for VSL compared to safety and efficiency aspects. Zegeye et al. (2011) have developed a control strategy based on model predictive control with one part of the objective to minimize emission levels. This study shows that there is a trade-off between low emission levels and traffic efficiency. By only considering environmental impacts the traffic efficiency might be substantially lowered.

Lu et al. (2011); Carlson et al. (2012) and Zhang et al. (2006) combine VSL system with a ramp metering system. This shows that VSL system are only effective up to a certain point, i.e. vehicles cannot disappear and by lowering the speed limit the vehicles are still present in the traffic system. If the traffic flow becomes very
Chapter 4. Variable speed limit systems

high this will eventually lead to a brake down. By also incorporating ramp metering, the inflow on the motorway can be controlled even further, resulting in additional improvements.
Chapter 5

A cooperative variable speed limit system

In this chapter a Cooperative Variable Speed Limit (C-VSL) system is proposed as an extension to an existing VSL system. The system is making use of I2V communication and the potential benefits of the system are investigated. Results related to traffic efficiency and environmental impacts are presented. In the proposed C-VSL system, the speed limits given to the vehicles are based on the speed and location of each single vehicle. Therefore, a detailed modeling of the individual vehicles within the simulation is required and a microscopic traffic simulation approach is applied for evaluation of the C-VSL system. Further, by the use of microscopic traffic simulation the traffic performance and the exhaust emissions can be evaluated on a more detailed level.

The proposed C-VSL system is introduced in Section 5.1. Section 5.2 describes how a regular VSL system and a C-VSL system can be modeled in the microscopic traffic simulator SUMO, including a description of the simulation scenarios, the system and vehicle parameter specific assumptions and the experimental setup. The results of the evaluation are presented in section 5.3. Finally, in Section 5.4 the main conclusions of the evaluation is given.
5.1 An I2V based cooperative variable speed limit system

In existing VSL systems, VSL signs are used for showing information about the speed limits to the drivers. A C-VSL system can be created by having the VSL signs functioning as roadside units, sending out information to the individual vehicles about speed limits via an I2V communication channel. An illustration on how the C-VSL system should work is given in figure 5.1. The arrows indicate how the variable speed limit information is communicated to the vehicles.

![Illustration of a cooperative variable speed limit system](image_url)

**Figure 5.1:** Illustration of a cooperative variable speed limit system

A simple approach have been used for modeling of the system, and where the assumptions about the system features are made as realistic as possible. The idea is to have a system that could be implemented in the vehicles by only using information from the roadside units that are implemented in VSL systems that exists today. The speed limits given to the vehicles are calculated based on: (1) the distance between the vehicle and the VSL sign showing the new speed, (2) the current speed of the vehicle and (3) the reference speed shown on the VSL sign. As a result of this approach, when the vehicles reach the new speed limits they have been given individual speed limits at predefined time intervals resulting in a smooth change in speed towards the new speed limit. The differences between the standard VSL system and the C-VSL system can be summarized by the following,

- With the C-VSL system, information about the variable speed limit is received at an earlier point in time.
5.1. An I2V based cooperative variable speed limit system

- With the C-VSL system, vehicles are given individual speed limits determined by their current speed and position.
- The C-VSL system is assumed to be implemented as an autonomous control system, i.e. no driver response is necessary to adapt to the individual speed limits. This can be achieved by integrating the C-VSL system function in the cruise control system of the vehicle.

The benefits with such an extension are summarized below,

- There is no need for roadside VSL signs displaying the speed limits. The VSL sign could be replaced by a roadside unit able to communicate the speed limits to each vehicle located upstream of the roadside unit by assuming complete coverage for equipped vehicles.
- The VSL is communicated to the vehicle before the driver can see the physical VSL sign, i.e. the vehicle has the possibility to adapt to speed limit changes earlier in time.
- The VSL given to the vehicle are individualized, meaning that the properties of the vehicle, i.e. the position on the road and the speed of the vehicle, could be taken into account.
- The system assumed to be autonomous, i.e. without interaction from the driver allowing for autonomous adaptation towards the communicated speed limits, and thereby the effects of different driving styles are limited.

To our knowledge, few studies exist on the potential benefits of a C-VSL system where I2V communication is introduced as an enhancement to a current VSL system.

A system related to the C-VSL system proposed is considered by Piao and McDonald (2008) where the VSLs are given to the driver through an in-vehicle application displaying the current speed limit on the road. In the study different penetration levels have been considered. The safety effects have been evaluated indicating reduction in variation of speed between detector stations, small time headways and reduced time-to-collision. A decrease in efficiency can also be noted due to longer travel times with decreased speed limits. The longer the controlled section are the more does the travel time increase. The in-vehicle application discussed in Piao and McDonald (2008) is a pure information system and does not take into account individual properties of the vehicles.
Chapter 5. A cooperative variable speed limit system

In Hegyi et al. (2013) a cooperative system based VSL control strategy is proposed as an extension to the SPECIALIST control strategy presented in Hegyi et al. (2008). The extension is used to detect shockwaves earlier by the use of floating car data and video-based monitoring. By using this kind of data shockwaves can be detected also in between detector stations, leading to faster activation of the system. The cooperative SPECIALIST has been evaluated by the use of a microscopic traffic simulator, indicating faster detection of shockwaves. The faster detection results in a reduction in time when the VSL signs are active, as well as a shorter application area with lower speed limits. This will obviously result in shorter delays compared to the regular SPECIALIST, but also compared to the uncontrolled case.

Modeling of a cooperative variable speed limit system

For the C-VSL system, the variable speed limits are used as reference speeds for calculations of the individual speeds that are given to the vehicles at specific points in time. The vehicles are assumed to receive updates of the speed limit information via communication with the roadside units during the whole road segment between consecutive VSL signs. The individual speed limits given by the C-VSL system to the vehicles are calculated based on the equations of motion, i.e. the acceleration needed to reach a given speed limit after a predefined distance taking into account the current speed of the vehicle. First, the constant acceleration needed to adapt to the given speed limit at the position of the next VSL sign is determined,

$$a_{t,i} = \frac{v_{t,j}^2 - u_{t,i}^2}{2 \cdot s_{t,ij}}, \quad (5.1)$$

where $v_{t,j}$ is the speed limit obtained from variable speed limit sign $j$ (located immediately in front of vehicle $i$) at time $t$, $u_{t,i}$ is the current speed of vehicle $i$ at time $t$ and $s_{t,ij}$ is the distance between vehicle $i$ and variable speed limit sign $j$. The acceleration is bounded to the interval between the drivers’ maximum desired acceleration and deceleration. The acceleration, given by Equation 5.1, is then used to determine the individual speed $\tilde{w}_{t,i}$, calculated based on the individual vehicles position and speed according to
5.1. An I2V based cooperative variable speed limit system

\[ \tilde{w}_{t,i} = u_{t,i} + a_{t,i} \cdot T, \]  

(5.2)

where \( T \) is the time interval between updates of the individual speed in the C-VSL system. To prevent low speeds, the individual speeds given to the vehicles are never below the current variable speed limit. Similarly, individual speeds above the maximum speed limit on the road are not given to the vehicles. The final individual speed, \( w_{t,i} \), is therefore given by

\[ w_{t,i} = \max (v_{t,j}, \min (\tilde{w}_{t,i}, V_{\text{max}})), \]  

(5.3)

where \( V_{\text{max}} \) is the maximum recommended speed set to be the maximum allowed speed on the road.

** Variable speed limit control algorithm **

The control algorithm used in both the C-VSL system and the VSL system are based on the aforementioned MCS system implemented in Stockholm, presented in Chapter 4. In the current system the algorithm for deciding on the speed limit does take into account mean speed. The mean speed at the detectors are calculated by the use of a smoothed harmonic mean speed given by

\[ \frac{1}{\tilde{v}_{t,j}} = \alpha \frac{1}{v_{\text{measured}}} + (1 - \alpha) \frac{1}{v_{t-1,j}}, \]  

(5.4)

where \( \tilde{v}_{t,j} \) is the calculated mean speed at time \( t \) and detector station \( j \). \( v_{\text{measured}} \) is the measured speed at the detectors and \( \alpha \) is the smoothing parameter which value range between 0 and 1 (van Toorenburg and de Kok, 1999). A smoothing parameter of 0.25 is used to take into account approximately the four last vehicles. The mean speed in 5.4 is calculated for each lane separately.

The maximum allowed speed limit on the road is assumed to be 120 km/h. The part of the algorithm used for deciding on the speed limit can be summarized by the following:

- If \( \tilde{v}_{t,j} \leq 45 \text{ km/h} \):
  - the speed limit at detector station \( j \) is updated to \( v_{t,j} = 60 \text{ km/h} \).
Chapter 5. A cooperative variable speed limit system

- the speed limits at the two upstream detectors are updated to $v_{t,j-1} = 80 \text{ km/h}$ and $v_{t,j-2} = 100 \text{ km/h}$. This might be changed later if also the next upstream detectors measure a mean speed below 45 km/h.

- If $\bar{v}_{t,j} \geq 55 \text{ km/h}$ and $v_{t,j} < 120 \text{ km/h}$:
  - the speed limit at detector station $j$ is updated to $v_{t,j} = 120 \text{ km/h}$
  - the speed limits at the two upstream detectors are updated to $v_{t,j-1} = 120 \text{ km/h}$ and $v_{t,j-2} = 120 \text{ km/h}$.

The speed limits and the thresholds described are based on a study of the existing MCS and the new speed limit system that is currently being implemented in Sweden (Lind and Strömgren, 2011). It is assumed that the most restrictive lane is regulating the speed limit, i.e. the lane with the lowest mean speed is considered when determining the speed limit for all lanes. The variable speed limits are updated every 4 seconds. The algorithm goes through all detectors starting from the most downstream detector included in the system.

The resulting traffic performance of the VSL and the C-VSL system are dependent on the choice of control algorithm. In Chapter 6 more elaborate control algorithms have been investigated and compared to the one presented here.

5.2 Evaluation method

For evaluation of a C-VSL system a comparison with a standard VSL system has to be done, and therefore both systems have to be implemented in the microscopic traffic simulation tool SUMO. The simulation scenarios and experimental setup has to be defined, and a set of assumptions has to be made. These assumptions concerns vehicle parameters and assumptions specific for the C-VSL system and the VSL system.

Modeling in SUMO

When a speed limit is changed the vehicles in the simulation need to receive and adapt to this information. One way to model this in SUMO is by modifying the maximum speed $v_{max}$ given in equation
3.3. The maximum speed is used for controlling of each vehicle’s individual maximum speed limit. By setting this speed limit to the speed limit currently applied on the road, or in the C-VSL system case the individual speed limit, the vehicles in the simulation do not override that speed limit. The maximum speed is distributed according to a normal distribution to capture different driving styles and different perceptions towards the shown speed limit on the road.

In the VSL system case the vehicles receive an updated maximum speed when they are assumed to see the VSL signs. In the C-VSL system case the vehicles receive information from an approaching VSL sign as soon as a new speed limit is applied, independent of where they are located on the road stretch. At each time step, a resulting modified desired speed is calculated and communicated to controlled vehicles by replacing $v_{max}$ in Equation 3.3 as

$$v_{des}(t) = \begin{cases} 
\min (v_{t,j}, v(t) + a(v)\Delta t, v_{safe}(t)), & \text{VSL system} \\
\min (w_{t,i}, v(t) + a(v)\Delta t, v_{safe}(t)), & \text{C-VSL system} 
\end{cases}$$

(5.5)

SUMO’s traffic control interface (TraCI) is used to get access to information in the SUMO simulation engine during the simulation runs. Python code is used to communicate with SUMO and for implementation of the C-VSL system and the VSL system. Figure 5.2 illustrates a general framework for implementation of the C-VSL system and the VSL system via communication with SUMO.

The network, demand and parameter files are produced separately and communicated to SUMO at the start of a simulation. Also, input parameters, such as car-following characteristics, speed distributions etc., are specified in the beginning of the simulation and communicated to SUMO via TraCI. During the simulation the TraCI is used to communicate speed from the detectors. Also, vehicle ID and lane ID used for accessing the vehicles’ current speed, current maximum speed and their location on a specific lane is communicated via TraCI. The new maximum allowed speed for the C-VSL system and the VSL system is calculated in the python script based on the detector data. Finally, the new maximum allowed speed for each vehicle in the simulation is communicated to SUMO via the TraCI and used in SUMO for calculating the desired speed in the car following model. The results from the simulation is collected as vehicle trajectories from SUMO via TraCI at one-second intervals and saved as xml-files.
xml-files includes: simulation time, vehicle ID, lane ID, lane position and speed.

**Simulation scenarios**

When studying the effects of a C-VSL system and the VSL system a realistic but yet simple traffic scenario is suitable to isolate the effects of the system extension. An open traffic system consisting of a stretch of motorway, without on- or off-ramps, is chosen for studying the effects of the C-VSL system and the VSL system. The reason for choosing this elementary design is to be able to easily evaluate the benefits of extending an existing VSL system with the autonomous C-VSL system including Infrastructure to Vehicle (I2V) communication. The simulated road is divided into eight 500 meter segments, with one detector and one VSL sign gantry per lane on each segment. The simulation is performed for a 20-minutes interval, excluding a warm-up period of 5 minutes to prevent loading effects. The input flow during the period is held constant at 4400 vehicles per hour, which is approximately 70% of the capacity. In order to get an activation of the C-VSL system and the VSL system an incident is
modeled 100 meters upstream of the last detector station by decreasing the speed on a 100 meter long segment, to around 25 km/h after 5 minutes. The speed decrease is active for 10 minutes. The effect of this is that the vehicles are slowing down and a queue starts to build upstream of the incident area reaching one or more of the detector stations. This will activate the C-VSL system and the VSL system in the simulation and an evaluation of the system performance can be made. See figure 5.3 for an illustration of the considered traffic scenario.

By modeling the incident in this manner, and not by closing a lane or by the use of an onramp which requires modeling of weaving behavior, the dependence of the results on the lane changing and merging models used in the simulation is limited.

System and vehicle parameter assumptions

When implementing the VSL system it is assumed that all vehicles follow the given speed limits and that the vehicles are able to read the speed limits shown on the gantries within a range of 150 meters. The distance is based on recommendations from Trafikverket (2008) regarding when roadside signs should be readable. Approaching vehicles, following the standard VSL system, are updating their maximum allowed speed, according to the current speed limit on the road, when located within this range.

When the C-VSL system is simulated in SUMO, TraCI is used to keep track of individual vehicles’ speed and position. The final indi-
individual speed, calculated according to equation 5.3, is communicated
to each vehicle based on these measures.

The vehicle parameters used in the simulation are set to default
values used in SUMO version 0.18.0, see SUMO (2013), except for
the speed deviation and the speed factor. Each vehicle is assigned an
individual speed factor, with which the maximum speed is multiplied,
representing their individual perceived maximum speed. The speed
factors for the VSL system are drawn from a normal distribution with
mean 1.05 and standard deviation 0.05. The speed of the C-VSL sys-
tem controlled vehicles are assumed to be autonomously controlled by
the system, meaning that the corresponding speed factors are drawn
from a normal distribution with mean 1.0 and standard deviation 0.0.
Vehicles are generated with exponentially distributed headways.

The randomness of the simulations performed is taken into con-
sideration by performing 15 replications of the simulation for all sim-
ulated scenarios.

The vehicle specific parameters used in CMEM have been adopted
for emission estimation based on the properties and assumptions of
the vehicles simulated in SUMO, i.e. the vehicles are assumed to be
of the normal emitting, catalyst equipped gasoline fueled, passenger
car type in CMEM.

Experimental setup

In the evaluation of the C-VSL system, the resulting acceleration
rate distribution, mean speed and standard deviation of speed are
compared to an existing VSL system. The results are based on vehicle
trajectories collected from SUMO during the simulation by use of the
TraCI. The emission levels presented, based on calculations from
CMEM, are HC, NO$_2$, and CO$_2$ emissions. The reason for this choice
is that the CO emission of modern engines is limited and that fuel
consumption is strongly correlated with the CO$_2$ emissions.

The acceleration distributions indicate how smooth the traffic
flows during the simulation period. The frequency of hard braking
and strong acceleration situations are reflected in the tails of the ac-
celeration distributions. Heavy tails indicates many hard braking and
strong acceleration situations. An light tailed acceleration distribu-
tion is therefore desirable in order to have a smooth traffic behavior.
The acceleration distributions presented are the result of the simu-
lated vehicles’ accelerations in each time step and for 15 replications
5.2. Evaluation method

of the simulation.

The mean speed profiles is a measure of traffic efficiency. A decreasing mean speed with the C-VSL system, compared to the VSL system indicates decreased traffic efficiency. Similarly, an increasing mean speed with the C-VSL system, compared to the VSL system indicates increased traffic efficiency. It is desirable to have comparable mean speed levels for the C-VSL system compared to the VSL system, but even better is of course if the traffic efficiency is improved by increasing the mean speed. The speed profiles are presented as means over the simulated road and calculated as rolling averages over 30 second intervals of the simulated time period. The standard deviation of speed is another measure of traffic performance, with high deviations of speed, the distribution of individual speeds among the vehicles on a road stretch is wide. Also the mean standard deviation of speed is presented as a rolling average over 30 second intervals. The standard errors of the means for the speed profiles are with respect to 15 replications of the simulation for each of the considered scenarios.

The C-VSL system is expected to result in lower levels of emissions compared to the VSL system. The emissions are presented as accumulated emissions over the simulated road and for the whole simulation time period. The confidence intervals for the emissions are calculated with respect to 15 replications of the simulation for each of the considered scenarios.

For the C-VSL system different update times $T$ can be applied, see Equation 5.2. Since the road segments are 500 meter, long update times may result in vehicles that pass more than one variable speed limit sign before the individual speed limit is updated. This is obviously undesirable and $T$ should consequently be chosen sufficiently short so that the individual speed limit is updated in each segment of the road. Three different update times have been considered, $T=0.1$ s, 1 s and 10 s.

When introducing new systems on the market, with a need for new technology and/or equipment, the penetration rates are often low in the beginning. A realistic assumption would therefore be that not all drivers will be equipped with the C-VSL system, especially at an early stage of the implementation phase. Different penetration rates of the C-VSL system have been investigated to be able to evaluate the effect of only a portion of the vehicles being equipped with the system.
5.3 Computational results

The C-VSL system is expected to improve the traffic conditions on the road by means of a smoother traffic flow, leading to less frequent high acceleration rates. This in turn would probably affect the emission levels positively. Another desired outcome of the C-VSL system is that the mean speed would increase or at least not decrease compared to the existing VSL system.

First, the effects of the C-VSL system compared to the standard VSL system are studied. Then, the sensitivity of the C-VSL system to the system update time is investigated and scenarios including different traffic penetration rates of the C-VSL system are analyzed. Finally, the main conclusions from the evaluation are given.

Comparison of the VSL system and the C-VSL system

The expectation is that the amount of high acceleration rates should increase for the VSL system compared to the C-VSL system. This is confirmed by the acceleration rate distributions in Figure 5.4. The update time for the C-VSL system is set to the simulation time step, i.e. $T=0.1$ s.

![Figure 5.4: Empirical acceleration density functions for the VSL system and the C-VSL system scenarios](image-url)
5.3. Computational results

A two-sample Kolmogorov-Smirnov test of the distance between the two empirical probability distributions confirms that the distributions are different, \( p < 0.001 \). Both the C-VSL system and the VSL system have accelerations centered around zero, but the VSL system result in higher amounts of high acceleration rates compared to the C-VSL system and a wider acceleration distribution.

The mean and standard deviation of speeds during the simulated time period for the VSL system and the C-VSL system scenarios are presented in Figure 5.5. The standard error of the means presented is less than or equal to 0.48 m/s and 0.39 m/s in all points for the mean speed and the mean standard deviation of speed, respectively.

![Figure 5.5: Mean speed (a) and mean standard deviation of speed (b) over all segments of the road for the VSL system and the C-VSL system scenarios.](image)

The figures show that the mean speed for the VSL system is slightly below the mean speed for the C-VSL system. As expected, the mean standard deviation of speed is higher for the VSL system compared to the C-VSL system, especially when the VSL signs are inactive. This is a result of the input desired speed distribution and the autonomous control of the C-VSL system equipped vehicles. When the VSL signs are active the mean standard deviation of speed becomes higher as a result of the differences in speed limits between different segments of the road. There is also a difference in mean standard deviation of speed during the incident when the VSL signs are active, indicating a contribution of the I2V communication part of the C-VSL system.

For the C-VSL scenario, oscillations appear when the VSL signs becomes active. This can be explained by the short update time
interval, $T = 0.1$ s, resulting in immediate response, and a degree of over-reaction, to speed limit changes by the vehicles in the simulation.

Table 5.1 gives an overview of the cumulative emission levels for the VSL system and the C-VSL system scenarios. The intervals given in the tables are standard normal distribution based confidence intervals at a 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>CO$_2$ (kg)</th>
<th>Diff (%)</th>
<th>HC (g)</th>
<th>Diff (%)</th>
<th>NO$_x$ (g)</th>
<th>Diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSL</td>
<td>1381±12</td>
<td></td>
<td>2164±26</td>
<td></td>
<td>3978±40</td>
<td></td>
</tr>
<tr>
<td>C-VSL</td>
<td>1359±17</td>
<td>1.6</td>
<td>1834±34</td>
<td>15.3</td>
<td>3605±53</td>
<td>9.4</td>
</tr>
</tbody>
</table>

Table 5.1: Emissions generated in the VSL system and the C-VSL system scenarios. For each type of emission, the mean emission is presented together with the difference between the VSL system and the C-VSL system scenarios.

Differences are found between the VSL system and the C-VSL system for all types of emissions presented. The differences are significant for HC and NO$_x$. For CO$_2$ the confidence intervals overlap indicating a non-significant difference.

**Sensitivity of the update time of the C-VSL system**

The sensitivity of the C-VSL system to the system update time, $T$, is investigated by analysis of scenarios with different update times. The update times considered are chosen so that vehicles receive at least one update of the individual speed in each segment of the road.

The distribution of acceleration rates for scenarios with different C-VSL system update times are shown in Figure 5.6. We conclude that the C-VSL system is not sensitive to changes in system update time in the range between 0.1 and 10 s.

The mean speeds and mean standard deviation of speeds during the simulated time period for the scenarios with different update time of the C-VSL system are presented in Figure 5.7. The standard error of the means presented is less than or equal to 0.49 m/s, and 0.38 m/s in all points for the mean speed and the mean standard deviation of speed, respectively. The oscillations observed when the VSL signs becomes active and for the update time $T = 0.1$ are decreasing with
5.3. Computational results

increasing update time. In other words, by increasing the C-VSL system update time the mean speed is becoming more stable. An update time $T=0.1$ s seems therefore to be too short.

The emissions for the scenarios with different C-VSL system update times are presented in Table 5.2. The intervals presented are standard normal distribution based 95 % confidence intervals of the means. There is a tendency for increased emission rates with increasing C-VSL system update time. The small effect sizes are in line with the expectations given by the acceleration distributions shown in Figure 5.6.

![Figure 5.6: Empirical acceleration density function for the C-VSL system with update times, 0.1 s, 1 s and 10 s.](image)

<table>
<thead>
<tr>
<th>C-VSL update time $T$ (s)</th>
<th>Mean CO$_2$ (kg)</th>
<th>Mean HC (g)</th>
<th>Mean NO$_x$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1359±17</td>
<td>1834±34</td>
<td>3605±53</td>
</tr>
<tr>
<td>1</td>
<td>1360±19</td>
<td>1844±38</td>
<td>3629±62</td>
</tr>
<tr>
<td>10</td>
<td>1364±17</td>
<td>1907±39</td>
<td>3693±59</td>
</tr>
</tbody>
</table>

Table 5.2: Emissions generated in the scenarios with different update times of the C-VSL system.

We conclude that the C-VSL system is robust to changes in update
time with respect to the resulting acceleration rates, vehicle speeds and emissions. A very short update time leads to oscillations in speed when the VSL signs becomes active. A longer system update time will be superior in this perspective.

**Effect of the C-VSL system penetration rate**

Investigation of scenarios including different C-VSL system traffic penetration rates are made by a similar set of comparisons as in section 5.3. Here an update time of \( T=1 \) s is used for the C-VSL system. The reason for choosing this update time is that the results from the previous analysis of the effect of the update time showed that this update time is long enough to prevent oscillations in speed after system activation. It can also be considered feasible to design an I2V communication system with an update time in the order of 1 s.

The expectation is that increasing the C-VSL system penetration rate, would result in a more narrow acceleration distribution. The results in Figure 5.8 are in line with this expectation.

Two-sample Kolmogorov-Smirnov tests confirm that the difference between all pairs of distributions are significant (\( p < 0.001 \)).

Figure 5.9 show the mean speed and the mean standard deviation of speed for the different C-VSL system penetration rate scenarios. The standard error of the means presented is less than or equal to 0.69 m/s and 0.52 m/s in all points for the mean speed and the mean standard deviation of speed, respectively.
5.3. Computational results

![Graph showing empirical acceleration density functions for C-VSL system penetration rates (pr) 100%, 70%, 50%, and 30%.](image)

**Figure 5.8:** Empirical acceleration density functions for C-VSL system penetration rates (pr) 100%, 70%, 50%, and 30%.

![Graph showing mean speed and mean standard deviation of speed over all segments of the road for scenarios with different C-VSL system penetration rate (pr).](image)

**Figure 5.9:** Mean speed (a) and mean standard deviation of speed (b) over all segments of the road for scenarios with different C-VSL system penetration rate (pr).
Chapter 5. A cooperative variable speed limit system

When the VSL signs are inactive, before and after the simulated incident, the mean standard deviation of speed becomes higher with lower C-VSL system penetration rates as expected. When the VSL signs are active and between time 15 and 20 minutes, the mean speeds for the 30 % and 70 % penetration rates scenarios are higher and lower than the mean speed of the 100 % penetration rate scenario, respectively. An investigation of the speed distribution on the individual segments of the road reveals that these results are due to equipped vehicles either disturbing or contributing to flow harmonization, depending on the penetration rate. In the 30 % penetration rate scenario, most vehicles follow the standard VSL system and the relatively few C-VSL system equipped vehicles contribute to reducing the variance in speed between lanes and thereby the need for lane-changing maneuvers that will disturb the flow. In the 70 % scenario, the few non-equipped vehicles will disturb the flow by changing lanes when the C-VSL system equipped vehicles start to decelerate to reach the new speed limit.

Since an increasing C-VSL system penetration rate was found to result in a narrowing of the acceleration distribution the expectation is that it will also lead to a decrease in emissions. The results shown in Table 5.3 confirms this expectation.

<table>
<thead>
<tr>
<th>C-VSL penetration rate (%)</th>
<th>Mean CO₂ (kg)</th>
<th>Mean HC(g)</th>
<th>Mean NOₓ(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1364±17</td>
<td>2056±31</td>
<td>3859±51</td>
</tr>
<tr>
<td>50</td>
<td>1363±29</td>
<td>2005±39</td>
<td>3803±63</td>
</tr>
<tr>
<td>70</td>
<td>1364±19</td>
<td>1967±43</td>
<td>3759±76</td>
</tr>
<tr>
<td>100</td>
<td>1360±19</td>
<td>1844±38</td>
<td>3629±62</td>
</tr>
</tbody>
</table>

Table 5.3: Emissions generated in scenarios with different C-VSL system penetration rate.

There is a tendency for reduced emissions with increasing C-VSL system penetration rates. Significant effects can be concluded for HC and NOₓ between the 100 % penetration rate scenario and the other scenarios. Comparing the 30 % C-VSL system penetration rate scenario to the 100 % scenario, there is a decrease of 10.3 and 6.0 % in HC and NOₓ emissions, respectively.

We conclude that increasing C-VSL system penetration rates contribute to a narrowing of the acceleration distribution and reduced
emissions. Concerning the vehicle speeds, in the studied 30 and 70 % penetration rate scenarios, there is an effect of vehicles of the minority in the flow either contributing to or disturbing the flow harmonization effect of the C-VSL system.

5.4 Conclusions

We have studied the potential benefits of I2V communication and autonomous control for variable speed limit systems (VSL systems) by proposing a cooperative systems extension (C-VSL system) to an existing VSL system. The effects of the proposed C-VSL system were analyzed by comparing the C-VSL system to the corresponding standard VSL system by means of traffic simulation.

The conclusion, based on the results of the simulation experiments, is that I2V communication and autonomous control can further contribute to flow harmonization and reduced exhaust emissions. The C-VSL system has been shown to result in a narrowing of the acceleration rate distribution compared to the existing VSL system and reductions in NO
\textsubscript{x} and HC emissions were established. Also safety is believed to be improved due to less high acceleration rates resulting in a more harmonized traffic flow.

The suggested C-VSL system is not sensitive to system update times shorter than a reasonable upper bound, corresponding to at least one update of the individual speed on each segment of the road. The effect of the C-VSL system is also found to increase with increasing traffic penetration rate of the system. However, in scenarios with relatively low and high C-VSL system penetration rate there was an effect on speed when the VSL signs were active in the form of increased and decreased mean speeds, respectively. This can be explained by vehicles of the minority in the flow either contributing to or reducing the variance in speed depending on if the minority or majority of the vehicles that make up the traffic flow are C-VSL system equipped.
Chapter 6

Comparison of variable speed limit control algorithms

The performances of the C-VSL system and the VSL system, evaluated in Chapter 5, are both dependent on the choice of control algorithm used for deciding which speed limit to be displayed on each road segment. Many control algorithms have been proposed in the literature with different objectives, as was discussed in Chapter 4.

The algorithms that are most probable to have success in real-world implementations are those that are simple but yet effective and where the calculations can be made fast while only requiring current data measured on the road. Four algorithms that meet these requirements are investigated in this chapter. The algorithms investigated are presented in van Toorenburg and de Kok (1999); Carlson et al. (2011); Hegyi et al. (2008) and Lee et al. (2006). The already implemented VSL systems are often based on simplistic rules, not necessarily reflecting the conditions on the road. Our hypothesis is that by finding a simple but yet effective VSL algorithm better reflecting the conditions on the road the traffic efficiency can be further enhanced. The aim of this investigation is to evaluate the performance of the four algorithms with respect to traffic efficiency. And also, to study the benefits and drawbacks of the four algorithms presented.

In order to investigate the algorithms a microscopic traffic simu-
Chapter 6. Comparison of variable speed limit control algorithms

lation approach is used. When evaluating the different algorithms it is important to find one scenario equal for all algorithms such that the algorithms are easily comparable. It is also important to find a scenario that reflects the reality as good as possible to be able to conclude how the algorithms will perform in real life. Congested situations, and especially merging behavior, are known to be hard to model and therefore extra consideration need to be taken regarding modeling of congested situations that will trigger the VSL algorithms.

The four control algorithms are described in Section 6.1-6.4. Issues regarding modeling of merging behavior in SUMO are discussed and investigated in Section 6.5. Section 6.6 describes how the four algorithms are modeled in SUMO, together with the basic assumptions, parameter values and algorithm specific assumptions. In Section 6.7 the results from simulations of a scenario, applying each algorithm, are presented and compared. Finally, the main conclusions are presented in Section 6.8.

6.1 Motorway control system

The first algorithm considered is the VSL algorithm included in Motorway Control System (MCS) (van Toorenburg and de Kok, 1999). This algorithm is based on the system implemented in the Netherlands (van den Hoogen and Smulders, 1994). The functionality of the algorithm was presented in Chapter 4. The algorithm is based on incident detection. An incident is assumed to have occurred when the mean speed at the detector stations falls below a predefined threshold. When an incident have occurred the speed limit on each road section affected by the incident is lowered by a fixed amount, predefined by the user. Lead-in speed limits are used upstream of the incident area based on predefined values set by the user. Figure 6.1 gives an illustration of a road stretch with an MCS algorithm implemented. In this case only one road section is affected by the lowered speed limits. It can also be the case that more road sections are affected from the start of the incident detection or after some time with the VSL signs active, until the congestion is resolved.

The incident is assumed to be present until the mean speed at the detector stations increase above another predefined threshold. When the incident is dissolved the speed limit is increased again to the original speed limit on the road. The thresholds for lowering and
6.2 Mainstream traffic flow control

In Carlson et al. (2011) an algorithm referred to as Mainstream Traffic Flow Control (MTFC) is proposed. It is well-known that the capacity in congested situations, and at bottleneck locations, tend to drop. The drop has been discovered in real traffic through empirical studies, see e.g. Srivastava and Geroliminis (2013); Chung et al. (2007) and Zhang and Levinson (2004). When the traffic flow reaches its maximum the traffic state becomes unstable resulting in a lower throughput of traffic than what can actually be achieved, i.e. a capacity drop occurs. In Carlson et al. (2011) the aim is to avoid the capacity drop by using an algorithm based on control theory. If the capacity level at a specific location is known the capacity drop is prevented by targeting a speed limit that keeps the density at its maximum.

In Carlson et al. (2011) a cascade controller is proposed for controlling the density. A primary controller is used to determine the outflow immediately after the bottleneck. The outflow, \( \hat{q}_c(t) \), at the bottleneck at time \( t \) is determined based on the measured density and a predefined threshold for the critical density by using an proportional-integral controller.

\[
\hat{q}_c(t) = \hat{q}_c(t-1) + \left( K'_{P} + K'_{I} \right) e_{\rho}(t) - K'_{P} e_{\rho}(t-1), \quad (6.1)
\]

where \( K'_{P} \) and \( K'_{I} \) is the proportional and integral gain, respectively, and \( e_{\rho}(t) \) is the density error calculated as the difference between the increasing the speed limits, as well as the predefined variable speed limit change and the lead-in speed limits, are depending on the original speed limit on the road. For further descriptions of the algorithm see chapter 4.
predefined threshold for density at capacity, \( \hat{\rho} \), and the measured density, \( \tilde{\rho}(t) \), at time \( t \). The predefined threshold for density at capacity is based on the specific bottleneck site, i.e. it can vary a lot between sites. It is therefore important to investigate a site before applying the algorithm.

In Carlson et al. (2011) the values of the gains have been tuned in such a way that the controller is representative and robust enough to handle several real-world conditions.

Finally, the speed limit is decided with the secondary controller which is an integral type controller, where the measured output flow is compared to the calculated desired output flow given in equation 6.1. The variable speed limit change at time \( t \) is calculated as

\[
b(t) = b(t - 1) + K'_I e_q(t),
\]

where \( K'_I \) is the integral gain and \( e_q(t) \) is the flow error calculated as the difference between the calculated reference flow, \( \hat{q}_c(t) \), and the measured flow, \( \hat{q}(t) \). To obtain the final speed limit, \( b(t) \) is multiplied with the maximum allowed speed limit on the road. Since it is usually easier to obtain occupancy than density from traffic measurements, occupancy can be used instead of density in Equation 6.1.

In Carlson et al. (2011) the MTFC have been investigated by the use of macroscopic traffic simulation. In a later study by Müller et al. (2013) the algorithm is evaluated by the use of microscopic traffic simulation. In Müller et al. (2013) the cascade controller is replaced with an integral controller. As mentioned before it is easier to obtain traffic measurements for occupancy than density, and the density measurements can be replaced by occupancy measurements. Therefore, the speed limit is determined by controlling the occupancy at the bottleneck towards the predefined critical occupancy. The variable speed limit change at time \( t \) is calculated as,

\[
b(t) = b(t - 1) + K'_I e_o(t),
\]

where \( K'_I \) is the integral gain and \( e_o(t) \) is the occupancy error calculated as the difference between the critical occupancy, \( \hat{o}_{out} \), and the measured occupancy at the bottleneck, \( \tilde{o}_{out}(t) \), at the time \( t \). According to Müller et al. (2013) this version of the algorithm is performing well and is therefore used for further investigation later in this chapter.
6.3. Speed controlling algorithm using shockwave theory

The final speed limit is applied to a VSL application area upstream of the bottleneck location. Just after the VSL application area an acceleration area is applied for the vehicles to be able to accelerate to the actual speed limit on the road before approaching the bottleneck location. Figure 6.2 gives illustration of a road stretch with an MTFC implemented. The length of the acceleration area and the VSL application area is decided by the user and should be based on tuning for the specific site. The magnitude of the speed limit within the VSL application area is based on how big the difference is between measured occupancy and the density at maximum occupancy, and is defined by Equation 6.3.

![Figure 6.2: Illustration of a road stretch with an MTFC algorithm implemented.](image)

The algorithm aims at controlling the flow by keeping it a capacity level at all times and can therefore be referred to as a harmonization algorithm.

6.3 Speed controlling algorithm using shockwave theory

The SPEed ControllIng ALgorIthm using Shockwave Theory (SPECIALIST) proposed by Hegyi et al. (2008), is an incident detection type of algorithm. The incident detection consists of detection of moving shockwaves by the use of speed and flow thresholds. If the head and tail of a shockwave can be detected the traffic states downstream, upstream and within the shockwave can be decided by the use of detector measurements. Calculations of the different traffic states is done by applying shockwave theory and by solving linear equations. By making use of variable speed limits the propagation of the shockwave can be prevented, and if possible resolved.

When interrupting the shockwave by applying variable speed lim-
its, six different traffic states are assumed to be present. The different states becomes present at different points in time during the shock-wave resolution process. These time points can be divided into four phases. See figure 6.3 for an illustration of the different phases and the states included in each phase.

Figure 6.3: Illustration of a road stretch with an SPECIALIST algorithm implemented.
6.3. Speed controlling algorithm using shockwave theory

The algorithm can be described based on its phases:

- **Phase 1**: The shockwave is detected based on thresholds for speed, \( v_{\text{max}} \), and flow, \( q_{\text{max}} \). The thresholds are compared to detector measurements on the road. This results in a start and end point of the congested state 2.

- **Phase 2**: Predefined speed limits set by the user are applied to state 2 and an additional stretch upstream of the congested state, state 3. Additionally, state 4 becomes present as a result of vehicles arriving to state 3 that are starting to slow down before entering state 3. The tail of state 4 will propagate upstream or downstream depending on the flow levels in state 4. Also in state 4, the predefined speed limits are applied along with the propagation of the tail. Lead-in speed limits based on predefined values are applied to two location upstream of the VSL application area. At the same time speed limits are turned off downstream as the congestion are dissolved and state 3 propagates upstream.

- **Phase 3**: Speed limits are applied to the tail of state 4 which is propagating upstream. At the same time speed limits are turned off at the head of state 4 which is also propagating upstream. Downstream of state 4 a discharging area is present, state 5, when the vehicles accelerate from speed levels corresponding to the speed limit in state 4 towards free flow.

- **Phase 4**: Eventually only state 5 remains together with the free flow states. No speed limit is applied. State 5 is propagating downstream until speed levels at maximum allowed speed limit on the road is obtained, and the control algorithm start to look for new shockwaves.

Figure 6.4 gives an illustration on how the states are related in a time-space diagram. A set of conditions related to each state and the relations between the states is used to determine if the shockwave is resolvable, see Hegyi et al. (2008). The conditions are necessary to be able to construct the characteristics of the diagram shown in Figure 6.4. If the detected shockwave is resolvable the different states needs to be defined in order to identify length of VSL application area and points in time when the VSL signs are turned on and off at specific detector locations. This is done by determining the speed, flow and density of each traffic state based on detector measurements, and
Chapter 6. Comparison of variable speed limit control algorithms

by calculating the slope between each state according to shockwave theory. The slopes between the states are seen in Figure 6.4.

Figure 6.4: Illustration of the different states of the SPECIALIST algorithm in a time-space diagram.

The different traffic states as well as measurements and calculations needed for determining the characteristics on each state are summarized below. It is assumed that detectors exists for each lane.

**State 1 and state 6**: State 1 and 6 are the upstream and downstream free flow states, respectively. The speed, flow and density of the states are based on detector measurements for speed and flow, and calculated as means of the speed and flow measurements from the detector stations included in each state. Since the density is not directly measured by the detectors it is calculated based on the flow and speed measurements, and the fundamental relations of speed, flow and density. The density is first calculated separately for each of the detector stations, and finally as a mean of the calculated density per detector station in each state.

**State 2** State 2 is representing the shockwave. The start and end of state 2 is dependent on the thresholds used for defining the shockwave. The flow of state 2 is based on detector measurements and calculated as for the free flow states. The density of state 2 at time $t$ is calculated as
6.3. Speed controlling algorithm using shockwave theory

\[ \rho_{t,2} = \rho_1 - \frac{q_{t,1} - q_{t,2}}{sw_{12}} \]  

(6.4)

where \( sw_{12} \) is the propagation speed of the shockwave, assumed to be a predefined input parameter based on empirical studies of the propagation speed of shockwaves. The reason for not using the detector measurements of speed when calculating the density is, according to Hegyi et al. (2008), that the low speed levels related to this state will give inaccurate estimates of the actual speed.

**State 3** State 3 is a result of the applied variable speed limit. When the speed is lowered on a road stretch the density is still the same as in state 6 but with a lower speed resulting in a lower flow. Therefore, the density of state 3 is the same as for state 6. The speed of state 3 is the same as the speed limit, set to a predefined value. The flow of state 3 is based on the speed and the density of state 3 together with the fundamental relations of speed, flow and density. As can be seen in Figure 6.4, the length of state 3 is decided based on the slope between state 2 and 3, and, state 3 and 4. The slopes are calculated based on speed, flow and density properties of the respective states together with applying shockwave theory and by solving linear equations.

**State 4** State 4 is representing the area just upstream of the speed limit area. In this area the speed is assumed to be in accordance with the predefined variable speed limit. The density of this state is typically higher than the density of state 3 (corresponding to density in free flow). The density in this area is not based on shockwave theory and is instead a design variable given as input to the algorithm. If the front of the state propagates upstream also the speed limit area will propagate upstream in this state, i.e. reduced speed limits are applied when the tail reaches a new VSL sign. The slope between state 4 and 6, shown in Figure 6.4, will determine how fast and how many VSL signs that are affected by the lowered speed limit.

**State 5** When the vehicles leave state 4 they will be able to increase their speed. The reason for this is that the density in this area is lower than in the shockwave, even though it is higher than in free flow. This state is called state 5. As a result, state 4 will eventually be resolved and the variable speed limits can be turned off as soon as state 5
Chapter 6. Comparison of variable speed limit control algorithms

reaches a VSL sign previously lowered in state 4. In state 5 both density and flow are design variables given as inputs to the algorithm. As can be seen in Figure 6.4, the slope between 4 and 5 determine how fast the VSL signs, previously turned on, will be turned off again.

There are some parameters used as input that has to be calibrated before implementation of the algorithm. These parameters have to be chosen carefully in order for the algorithm to be robust and effective. The thresholds for detecting a shockwave, $v_{\text{max}}$ and $q_{\text{max}}$ are two such parameters. Other parameters are the predefined variable speed limit, an additional margin for the head and the tail of the shockwave, the density of state 4, and flow and density of state 5. In Hegyi et al. (2008) and Hegyi and Hoogendoorn (2010) some of the parameters are based on empirical studies. For example the propagation speed of the shockwave and the speeds and densities used as design variables in state 4 and 5 can be based on offline data of previously detected conditions on the states. The parameters are then fine tuned based on the first settings.

6.4 Reducing crash potential

The Reducing Crash Potential (RCP) algorithm is different from the three previously presented algorithms. The aim of the algorithm is to reduce the risk of a crash by lowering the speed limits on the road at a predefined location known to have high crash risk. This is achieved by calculating the crash potential using a log-linear regression model. The model for calculating the crash potential have been developed in Lee et al. (2003) and applied to a VSL system in Lee et al. (2004) and Lee et al. (2006).

In the algorithm, the crash potential is calculated based on crash precursors and external control factors. The following steps are included in the algorithm:

1 Calculation of crash precursors based on detector measurements, and calculations of external factors based on conditions on the road, etc.

2 Categorization of the crash precursors. A number of discrete levels are set up to reflect how the crash precursors affect the final crash potential, i.e. how high the risk of an incident is
6.4. Reducing crash potential

based on each crash precursor. Thresholds are used to determine under which level each crash precursor is categorized.

3 The total crash potential is calculated. The levels determined in the previous step are used to assign values for each crash precursor contributing to the total crash potential.

4 The speed limit for each section included in the algorithm is decided based on the total crash potential and a predefined threshold set to represent situations when the total crash potential might lead to risky situations.

In the first step of the algorithm the crash precursors are calculated based on measurements at each detector location \( i \), as an average of the detector stations \( j \) located on each lane. The crash precursors taken into account are:

- The temporal variation of speed at detector location \( i \) and time \( t \) calculated as

  \[
  CVS_{t,i} = \frac{1}{n} \sum_{j=1}^{n} \frac{(\sigma_s)_{t,ij}}{\tilde{v}_{t,ij}},
  \tag{6.5}
  \]

  where \((\sigma_s)_{t,ij}\) and \(\tilde{v}_{t,ij}\) are the standard deviation of speed and the mean speed, gathered from detector station, \( j \) and at detector location \( i \). \( n \) is the total number of lanes, or corresponding detector stations, at detector location \( i \).

- The spatial variation of speed at detector location \( i \) and time \( t \) is calculated as

  \[
  Q_{t,i} = |\tilde{v}_{t,i-1} - \tilde{v}_{t,i+1}|,
  \tag{6.6}
  \]

  where \(\tilde{v}_{t,i}\) is the average speed at detector location \( i \) and time \( t \). The average speed is calculated as \(\tilde{v}_{t,i} = \frac{1}{n} \sum_{j=1}^{n} \tilde{v}_{t,ij}\), where \(\tilde{v}_{t,ij}\) is the detector measurements from detector station \( j \) and at detector location \( i \).

- The lane changing behavior at detector location \( i \) at time \( t \), based on the covariance of the volume difference at upstream and downstream locations, is calculated as

  \[
  COVV_{t,i} = \frac{1}{n} \sum_{j=1}^{n-1} cov (\Delta q_{t,ij}, \Delta q_{t,ij+1}),
  \tag{6.7}
  \]
where $\Delta q_{t,ij}$ is the difference in volume between upstream and downstream detector locations $i$ and detector station $j$, i.e. $\Delta q_{t,ij} = \tilde{q}_{t,i} - \tilde{q}_{t,i+1}$, where $\tilde{q}_{t,ij}$ is the volume measurement at detector location $i$ and detector station $j$.

The external factors included are: geometry, $R$, representing a merging or non-merging section and peak or off-peak traffic pattern, $P$.

In step 2, the crash precursors, $c$, are categorized into different discrete levels, $l_c$. For example crash precursor $CVS_{t,i}$ might have three levels, i.e. $l_{CVS}=$low, medium and high. The low level represent a value of $CVS$ where crashes are unlikely to occur and the high level represent a value of $CVS$ where crashes are likely to occur.

In step 3, the total crash potential at time $t$ and detector location $i$, equivalent to the total crash frequency, is calculated as

$$\ln (F_{t,i}) = \hat{\Theta} + \lambda_{CVS_{t,i}}(l_{CVS}) + \lambda_{Q_{t,i}}(l_Q) + \lambda_{COVV_{t,i}}(l_{COVV}) + \lambda_{R_{t,i}}(l_R) + \lambda_{P_{t,i}}(l_P),$$

(6.8)

where $\hat{\Theta}$ is a constant dependent on the data used for calibration. $\lambda_{CVS_{t,i}}(l_{CVS}), \lambda_{Q_{t,i}}(l_Q)$ and $\lambda_{COVV_{t,i}}(l_{COVV})$ are the estimated parameters representing the effect the crash precursors $CVS$, $Q$ and $COVV$ will have on the total crash potential for different levels, $l_{CVS}$, $l_Q$ and $l_{COVV}$. $\lambda_{R_{t,i}}(l_R)$ and $\lambda_{P_{t,i}}(l_P)$ is the effect of the external factors $R$ and $P$ for different levels, $l_R$ and $l_P$.

The estimated parameter values deciding the total crash potential in equation 6.8 are estimated based on crash and traffic data. The final number of categorizations and threshold values used are the result of best-fit of the log-linear regression model compared to the calibration data used. See Lee et al. (2003) for further descriptions of the final set of parameter values.

In step 4, the total crash potential for each detector location $i$ is compared to a predefined threshold representative for high crash risk situations. The speed limits are lowered if the total crash potential at a detector location is above the threshold. One way of calculating the displayed speed limit is based on the so called transition speed presented in Lee et al. (2006). The variable speed limit, $v_j$, at detector station $j$, is calculated as,
6.5 Merging behavior in microscopic traffic simulators

\[ v_j = \frac{\bar{v}_{j-1} + \bar{v}_{j+1}}{2}, \]  
\[ (6.9) \]

where \( \bar{v}_j \) is the mean speed measured at detector station \( j \). Other methods for calculating the displayed speed limit are discussed in Lee et al. (2006).

Figure 6.5 gives an illustration of a road section with an RCP algorithm implemented. In this case only one road segment is defined to have a high crash risk, i.e. the segment closest to the bottleneck location. The algorithm could be assigned to more sections, but with a large VSL application and thereby many VSL signs there is a risk of high difference in mean speed between segments, which contradicts the goal of the algorithm of lowering the total crash potential by harmonizing the flow. In Lee et al. (2006) only two detectors and VSL signs have been used and applied to the segments that are assumed to have the highest crash risk. It is recommended that one VSL sign upstream of the high risk area should show a lower speed limit to reduce speed variations between upstream approaching vehicles and vehicles within the VSL application area. This speed limit can be compared to the lead-in speed limits in previously discussed VSL systems, such as for example the MCS discussed in Section 6.1 and the SPECIALIST discussed in Section 6.3. Also the lead-in speed limits are based on transition speed according to Equation 6.9.

![Figure 6.5: Illustration of a road stretch with an RCP algorithm implemented.](image_url)

6.5 Merging behavior in microscopic traffic simulators

The modeling of merging behavior plays an important role in microscopic traffic simulation tools. A realistic way of modeling the merging
behavior is essential to get simulation results that are comparable to real world traffic conditions. Modeling of VSL systems require congestion with some type of merging situation in order for the system to be activated, i.e. for the speed limits to be lowered. The microscopic traffic simulation tool used for modeling the VSL system algorithms presented in this thesis is SUMO. An investigation of how SUMO performs with respect to modeling of merging situations is therefore crucial for the simulation study, and in order to get realistic results.

A congested traffic situation can be created in various ways. Three such ways are,

1. by the use of a lane drop.
2. by the use of an on-ramp.
3. by lowering the speed limit on a short segment during some time, and for one or more lanes, to represent an incident.

Each of the approaches mentioned above have its own implications for the modeling in SUMO. By visual inspection, and by investigation of the output from the simulations, an evaluation can be performed studying how satisfactory each approach is for modeling of congested situations. The parameters used in the car-following model are studied and possibly changed for all approaches to better reflect reality.

When evaluating each scenario it is important to obtain realistic flow levels. As mentioned before, field studies have concluded that during congested situations the capacity of the road is reduced resulting in the so called capacity drop, see e.g. Srivastava and Geroliminis (2013); Chung et al. (2007) and Zhang and Levinson (2004). In order for the simulation model to be realistic, similar behavior should be observable from the simulation output as well. The magnitude of the capacity drop should be in the same size as observed in field studies.

Results from the simulation of the different scenarios are summarized below:

- Lane drop - modeled by decreasing the number of lanes from three to two lanes:
  - With the standard parameters used in SUMO, the acceleration ability of each vehicle within the simulation is set to 2.6 m/s². This tends to give a too good performance of the vehicles within the simulation, resulting in a queue discharging rate not representative for reality. Therefore an
6.5. Merging behavior in microscopic traffic simulators

maximum acceleration of 0.8 m/s$^2$, as suggested in Krauß (1998), is used.

- The leftmost and the middle lane just before the lane drop are affected the most by the lane drop. This means that vehicles driving in the leftmost lane tries to change lane to the middle lane and a queue starts to build up. In the middle lane a queue is also starting to build up as a result of the merging vehicles coming from the leftmost lane. The rightmost lane continues to flow without much influence from the other lanes. This behavior is undesirable since it is not realistic to have very high speed levels on one lane and low speed levels or congested situations on the other lanes. By changing the reaction time from 1.0 s to 1.3 s the behavior becomes more realistic with respect to queue build-up and with more equal distribution of speeds between lanes. The reason for this is that vehicles need longer times to react. Thereby, they start to decelerate earlier when approaching a congested situation, which in turn lead to that queues start to build up in a more realistic way. And also, slow vehicles changing lane from the leftmost to the middle lane and from the middle lane to the rightmost lane have a lower acceleration rate. As a result the discharge rate of the queue is lower, and also, approaching vehicles slow down earlier. As a conclusion the vehicles within the traffic flow does not adapt as fast to surrounding traffic when the reaction time set to 1.3 s, which better reflect real-world conditions.

- Also, by changing reaction time from 1.0 s to 1.3 s the capacity drop and the flow levels becomes closer to results from field studies.

- On-ramp:

  - The reaction time affects the merging behavior. With lower reaction times the vehicles from the on-ramp is entering the motorway faster, as vehicles in the main lanes are moving away in order to let vehicles from the on-ramp enter the motorway. This is resulting in a realistic merging behavior. But, lower reaction times increase the capacity on the road and the leftmost lane get unrealistically high flow levels.
Chapter 6. Comparison of variable speed limit control algorithms

- Keeping the maximum acceleration ability low results in decreased capacity levels, while keeping the maximum acceleration ability high increases the capacity levels. 0.8 m/s\(^2\) seems too be to low and around 1.5 m/s\(^2\) seems reasonable. On the other hand, with a higher maximum acceleration ability the capacity drop is absent.

- The vehicles in the leftmost lane tend to flow without being affected by the ones in the other lanes irrespectively of the choice of parameters.

- It is hard to model realistic flow levels and a capacity drop at the same time.

• Incident modeling:
  - By reducing the speed limit on one or more lanes the vehicles starts to slow down before the incident area and start to accelerate after the incident area in a smooth way. This results in a too well-behaved situation, which is not realistic in real world situations. As a result, the capacity drop seen in real world situations is not observable.

As a conclusion the lane drop situation with a maximum acceleration ability set to 0.8 m/s\(^2\) and a reaction time set to 1.3 seconds seems to give the best results when compared to empirical studies and by visual inspection of the simulation. Although, there are still situations where vehicles in the rightmost lane tend to drive too fast compared to what would be expected from real world behavior. Although, the situations are not as frequent as with the standard value of reaction time. Figure 6.6 shows the flow-density relations when using a lane drop approach to simulate congestion. Each data point represent one simulation run and the flow and occupancy is based on a mean over a 15 minutes interval.

The capacity drop occurs at an occupancy level of around 14 %. This is somewhat higher compared to what have been found in the empirical study of capacity drops on a motorway in U.S. by Srivastava and Geroliminis (2013), but is still in a reasonable range. The capacity drop in the empirical study occur at a density of around 25 veh/km/lane. If it is assumed that the length of a vehicle is 5 meters, as is the case in the simulation, the resulting occupancy becomes \(5 \cdot 25/1000 \approx 12.5\ %\).

The capacity drop detected from the simulations is ranging between 2.5 % and up to 12 %, depending on how the graph is inter-
6.6 Evaluation method

For evaluation of the control algorithms, comparisons with a base case, without the algorithms being implemented are performed, and also, comparisons between the algorithms are carried out. In the simulation a set of conditions has to be defined. These conditions includes the base case scenario, vehicle parameters and assumptions specific for each of the algorithms implemented.

Modeling of control algorithms in SUMO

When a speed limit is changed, the vehicles in the simulation need to receive and adapt to this information. Since the speed limit is the same for all vehicles in the simulation, and not based on individual speed limits, as was the case for the C-VSL system described in Chapter 5, it is possible to just change the speed limits at each segment. The reason for doing this is to speed up the simulation. Simplifying
by changing the speed limit per segment does only involve one operation per lane and segment, instead of assigning each vehicle within the simulation a new speed limit. The simplification can be seen as having lots of VSL signs on each segment, all showing the same segment speed limit. This is not realistic but since the modeling is the same irrespective of algorithm it does not affect the comparison. Also, it does only affect the vehicles being on a segment when a speed limit change occur. After that each vehicle approaching a new segment can be assumed to see the correct speed limit value on the VSL sign.

The SUMO TraCI is used only for communicating the speed limits applied on each road segment, and for accessing the mean values gathered from the detectors.

Base case - simulation scenario

A base case is set up, which is the same for all four algorithms. The base case is constructed of a three-lane road stretch without on- and off-ramps. A bottleneck location is modeled by decreasing the number of lanes from three lanes to two lanes. The simple design makes it possible to isolate the effects of the algorithms. The simulated road is divided into fourteen 500 meter segments. The maximum allowed speed limit on the road is assumed to be 120 km/h. The number of detectors and VSL signs used for calculating and displaying lower speed limits are different depending on algorithm. Figure 6.7 gives an overview of the simulation scenario used for the four algorithms. Apart from the segments included in the evaluation a start and end segment, and two dummy stretches are included.

The simulation is performed for a 55-minutes interval, excluding a warm-up period of 5 minutes to prevent from loading effects. The input flow is held at 1500 veh/h for 10 minutes. In order to get an activation of the algorithms the flow is increased to 4500 veh/h for 15 minutes, which is approximately 70% of the capacity of three lanes. The flow is decreased again to 1500 veh/h for 30 minutes in order for the congestion to be resolved and the VSL signs to become inactive again.

The detector values used for deciding on speed limit to be displayed on the VSL sign are based on smoothed mean speeds over 30 second intervals irrespective of algorithm, and the speed limits are updated every 30 seconds. The smoothed mean speed is calculated as
6.6. Evaluation method

Figure 6.7: Illustration of the simulation scenario used for evaluation of the four control algorithms. The numbers refer to segments.

\[ \tilde{v}_{t,j} = \alpha v_{\text{measured},j} + (1 - \alpha) \tilde{v}_{t-1,j}, \]

(6.10)

where \( v_{\text{measured},j} \) is the measured mean speed at detector station \( j \), and \( \alpha \) is the smoothing factor set to 0.5.

The randomness of the simulations is taken into consideration by performing 20 replications of the simulation for all simulated scenarios.

System and vehicle parameters

Both system and vehicle parameters have to be considered when implementing the different VSL systems. Assumptions regarding the vehicle parameters are the same irrespective of VSL system. But the other parameters vary between VSL systems.

Vehicle parameters

The maximum acceleration ability is set to 0.8 m/s and the reaction time is set to 1.3 seconds based on the discussion in Section 6.5 regarding merging behavior. The desired speed factors are drawn from a normal distribution with mean 1.0 and speed deviation 0.1, based on a study by Varedian (2013). The study considered the speed distribution on 120 km/h roads for all vehicle types in Sweden. Thereby a normal composition of vehicle types is assumed. Differences in length are, however, not considered. Remaining vehicle parameters used in the simulation are set to default values used in SUMO version 99.
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0.19.0, see SUMO (2013). Vehicles are generated with exponentially distributed headways.

Motorway control system

For the VSL system included in the MCS, one detector and one VSL sign is applied for each lane and each segment, resulting in fourteen equipped segments. The algorithm used for deciding on speed limit, $v_{t,j}$, at time $t$ and detector location $j$ are based on the detector measurements over 30 second intervals, $\bar{v}_{t,j}$, and are summarized in the following bullets:

- If $\bar{v}_{t,j} \leq 45$ km/h:
  - the speed limit at detector station $j$ is updated as $v_{t,j} = 60$ km/h.
  - the speed limits at the two upstreams detectors are updated as $v_{t,j-1} = 80$ km/h and $v_{t,j-2} = 100$ km/h.

- If $\bar{v}_{t,j} \geq 55$ km/h and $v_{t,j} < 120$ km/h:
  - the speed limit at detector station $j$ is updated as $v_{t,j} = 120$ km/h
  - the speed limits at the two upstreams detectors are updated as $v_{t,j-1} = 120$ km/h and $v_{t,j-2} = 120$ km/h.

The thresholds are based on a study of the existing MCS and the new speed limit system that is currently being implemented in Sweden (Lind and Strömgren, 2011). It is assumed that the most restrictive lane is regulating the speed limit, i.e. the lane with the lowest mean speed is considered when determining the speed limit for all lanes. The algorithm goes through all detectors starting from the most upstream detector included in the system. 14 detectors located 500 meters apart from each other are included in the system.

Mainstream Traffic Flow Control

For the MTFC algorithm, the bottleneck location has to be defined. It is assumed to be located where the number of lanes change from three lanes to two lanes. The capacity level of the occupancy is set to 13%, based on the investigation of merging behavior in Section 6.5. The threshold is set somewhat lower than the critical capacity level of occupancy to limit the risk of exceeding the threshold. The
6.6. Evaluation method

integral gain, $K'_I$, is set to 0.005 based on Carlson et al. (2013). A minimum value of $b$ is set to 0.2 and a maximum value of $b$ is set to 1.0. The displayed speed limit is restricted to round-offs of 10 km/h, to have realistic values of the displayed speed limits. Four detectors are included in the system and located around the bottleneck. The final measured occupancy used in the algorithm are the maximum of the occupancy measurements for the included detector stations. The application area is set to 300 meter and the acceleration area is set to 275 meter based on recommendations from Carlson et al. (2013).

**SPECIALIST**

In the SPECIALIST algorithm a number of parameters and thresholds have to be defined. The thresholds and parameters are based on parameter settings 2 in Hegyi and Hoogendoorn (2010). The thresholds for identifying a shockwave are based on speed and flow. These levels are set to $v_{max} = 50$ km/h and $q_{max} = 1500$ veh/hour/lane. The assumed propagation speed of a shockwave is set to $sw_{12} = 18.1$ km/h. The design variables for state 4 and state 5 are set to $\rho_4 = 27$ veh/km/lane, $\rho_5 = 2060/93 = 22.15$ veh/km/lane and $v_5 = 93$ km/h. The additional margin for the head and the tail of the shockwave is set to $x_{head-offset} = 0$ km and $x_{tail-offset} = -1.25$ km, respectively. The predefined speed limit is set to 60 km/h. 14 detectors located 500 meters apart from each other are included in the system.

**Reducing Crash Potential**

The set of parameters used in the simulation are based on the calibration, and the near-optimal set of parameters, presented in Samimi and Hellinga (2012) and Hellinga and Samimi (2007). The resulting parameters are as follows: $\Theta = 1.929$, $\beta = 0.049$, $CVS_{low} = -2.132$, $CVS_{medium} = -2.107$, $CVS_{high} = 0$, $Q_{low} = -2.452$, $Q_{medium} = -2.107$, $Q_{low} = 0$, $COVV_{low} = -2.132$, $COVV_{medium} = -2.107$, $COVV_{high} = 0$. The external factors are set to $R_{straight} = -0.618$, $R_{merging} = 0$, $P_{off-peak} = -1.544$ and $P_{peak} = 0$. It is assumed to be peak-hour during the whole simulation period. The calibration data is based on 910000 veh·km. The threshold used for lowering the speed limits are based on Lee et al. (2006) and are set to $\bar{F}_M = 12$ for merging sections and $\bar{F}_S = 2.75$ for straight sections. The intervention time, i.e. the time the lower speed limits are displayed, is set to 10 minutes. The crash risk is assumed to be highest just before the bottleneck, and therefore the VSL is applied to that section. One
section upstream of the high risk section is used as a lead-in speed limit, as described in Section 6.4. The final speed limit displayed at the VSL signs are round-offs of 10 km/h, to have realistic values of the displayed speed limits.

**Performance indicators**

The effectiveness of the different algorithms are measured by the mean speed over the simulated road. The mean speed is calculated as a rolling average over 30 second intervals. A more detailed investigation of each of the algorithms is carried out by examining the mean speeds at the different detector stations, especially the detector stations close to the bottleneck are of interest. The mean speed are based on the measurements at each detector station calculated as in Equation 6.10. The means and standard errors of the means are calculated with respect to 20 replications for the base case and each of the VSL systems considered. When assigned speed limits at different points in time, they are presented as means of the 20 replications. Also standard errors of the mean speed limits are calculated with respect to 20 replications.

### 6.7 Computational results

In this section the computational results of the comparison of the algorithms are presented. First, an overall comparison of the algorithms are presented, followed by results from each of the investigated algorithms. Finally, the main conclusions of the comparison is summarized.

**Comparison between algorithms**

Figure 6.8 shows the mean speed for the whole stretch. The base case without applying a VSL algorithm is plotted together with the four other algorithms. The standard error of means presented is less than or equal to 1.15 m/s. From the figure it is concluded that only one algorithm, the MTFC, manage to increase the mean speed compared to the base case during congested conditions. The other algorithms are all below mean speed most of the time compared to the base case during congested conditions. Both the standard MCS and the RCP algorithms are slightly below the base case when the queue is building
up and until the flow is decreasing again, and the queue starts to dissolve. The same holds for the SPECIALIST algorithm, except for the most congested situations where the algorithm manages to keep a mean speed that is somewhat higher than the base case. After that the recovery rate is dependent on algorithm. The SPECIALIST and the RCP algorithms have the slowest recovery rates, followed by the MCS. The recovery rates of the SPECIALIST and the RCP algorithms are comparable. The results from the different algorithms are discussed in more detail in the sections below.

![Graph showing mean speed over time for different algorithms.](image)

**Figure 6.8:** Mean speed over the whole stretch for the base case and the different algorithms.

### MCS

The VSL algorithm included in the MCS is the algorithm using the most simplistic rules. This is also reflected in the results since the algorithm tends to have a mean speed slightly below the other algorithms under congested conditions. By looking at the mean speed for each detector station as in figure 6.9, it is also concluded that the mean speed at all detectors is lower compared to the base case.
Also, a larger area is affected by lower mean speed compared to the base case. This is a result of the lead-in speed limits, which aims at reducing high acceleration levels and thereby enhance safety. The standard error of means presented are less than or equal to 1.55 m/s. In the figure the mean speed ranges from 5 (dark red) to 35 (dark blue) m/s and the horizontal lines represent the location of detector stations from where the measurement data are collected.

The algorithm recovers faster towards original speed levels than the SPECIALIST algorithm and the RCP algorithm. This is due to that the speed limit is increased as soon as the mean speed at the detector stations are above the threshold used for increasing the speed limit.

![Figure 6.9: Mean speed at the detector stations for the base case and the MCS algorithm, respectively.](image)

Figure 6.10 gives an illustration of the mean speed limits over the 20 simulation runs. The speed limit area of 16.7 m/s (60 km/h) is propagating upstream along the stretch during the high flow period. This is the result of many vehicles arriving, which causes congestion and trigger the VSL signs further upstream. The lead-in speed limits are also visible in the figure in the limit between free flow speed levels and the speed limit levels of 16.7 m/s (60 km/h). The standard error of means presented are less than or equal to 1.86 m/s. The scale and the detector locations are the same as in previous figure.
6.7. Computational results

The aim of the MTFC is to keep flow at capacity levels and the algorithm seems to serve its purpose. The mean speed over the whole stretch, as well as for each detector station, as showed in Figure 6.11, are substantially higher in the MTFC case compared to the base case. In the congested situation the mean speed are kept at around 25 m/s compared to the base case where the mean speed ranges between 10 m/s to 20 m/s depending on detector station. The standard error of means presented are less than or equal to 1.95 m/s. The scale and the detector locations are the same as in the MCS section.

The speed limit is decreasing along with the duration of the congestion and is at a minimum lowered to around 24 m/s (86 km/h) in average over 20 simulation runs. Although, it can be lower for a single simulation run. See Figure 6.12 for an illustration of the speed limit levels at different points in time. The speed limit area is restricted to the application area. The standard error of means presented is less than or equal to 2.14 m/s. The scale and the detector locations are the same as in the MCS section.

Figure 6.10: Mean speed limit at the detector stations for the MCS algorithm.

MTFC

The aim of the MTFC is to keep flow at capacity levels and the algorithm seems to serve its purpose. The mean speed over the whole stretch, as well as for each detector station, as showed in Figure 6.11, are substantially higher in the MTFC case compared to the base case. In the congested situation the mean speed are kept at around 25 m/s compared to the base case where the mean speed ranges between 10 m/s to 20 m/s depending on detector station. The standard error of means presented are less than or equal to 1.95 m/s. The scale and the detector locations are the same as in the MCS section.

The speed limit is decreasing along with the duration of the congestion and is at a minimum lowered to around 24 m/s (86 km/h) in average over 20 simulation runs. Although, it can be lower for a single simulation run. See Figure 6.12 for an illustration of the speed limit levels at different points in time. The speed limit area is restricted to the application area. The standard error of means presented is less than or equal to 2.14 m/s. The scale and the detector locations are the same as in the MCS section.
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Figure 6.11: Mean speed at the detector stations for the base case and the MTFC algorithm, respectively.

Figure 6.12: Mean speed limit at the detector stations for the MTFC algorithm.
SPECIALIST

The traffic performance measured as mean speed over the whole stretch is lower for the SPECIALIST algorithm compared to the base case, except for in the most congested period. In Figure 6.13 the mean speed per detector station is presented. The standard error of means presented is less than or equal to 1.35 m/s. The scale and the detector locations are the same as in the MCS section. The mean speed are lower for most detectors, as a result of the lowering of speed limits upstream of the congestion, but close to the bottleneck the mean speed is actually higher during the congested situation, see the area from 4.5-6 km. The duration for lowering of speed limits is long which lead to a slow recovery rate towards the original mean speed on the road. And also, the stretch for which the speed limits are applied is long. It is first at detector station 1 the speed limit is kept at original speed limit on the road for the whole simulation period. During phase 3 the VSL signs are turned off as the boundary between state 4 and 5 propagate upstream. This is visible in the figure where free flow speed levels are seen from around 30 to 40 minutes, affecting detector stations in the area of 3-5 km.

Figure 6.13: Mean speed at the detector stations for the base case and the SPECIALIST algorithm, respectively.

Figure 6.14 shows the mean applied speed limit of the algorithm as calculated over 20 simulation runs. The standard error of means presented is less than or equal to 1.86 m/s. The scale and the detector locations are the same as in the MCS section. The stretch for which
the speed limits are applied are shown, as well as the time when the lowered speed limits are turned off along with the propagation of the boundary between state 4 and 5. Also, the lead-in speed limits are visible in the limit between free flow speed levels and the speed limit levels of 16.7 m/s (60 km/h).

![Figure 6.14: Mean speed limit at the detector stations for the SPECIALIST algorithm.](image)

**RCP**

The aim of the Reducing of crash potential algorithm is to keep crash potential low, and not to increase efficiency. Thereby, a decrease in mean speed is probable due to that a lower speed level might decrease the crash potential. As can be seen in Figure 6.15 the mean speed at detector stations 10 and 11 (around 5-6 km), where the speed limits are lowered during congested condition, are lower compared to the base case. But also the mean speed at detector stations close to the lowered speed limit area are decreased compared to the base case. In other words, the RCP algorithm does not result in increased traffic efficiency such as higher throughput of the traffic flow and increased mean speed. The standard error of means presented is less than or equal to 1.44 m/s. The scale and the detector locations are the same as in the MCS section.

The speed limit, based on a mean over 20 simulation runs, is lowered to around 19 m/s (70 km/h) at most for both detector stations as can be seen in figure 6.16. The standard error of means presented
6.7. Computational results

Figure 6.15: Mean speed at the detector stations for the base case and the RCP algorithm, respectively.

is less than or equal to 1.56 m/s. The scale and the detector locations are the same as in the MCS section. The speed limit is lowered for 10 minutes and then a new evaluation of crash risk is performed. This is also the reason for why the speed limit is of the same magnitude for a long time period.

Figure 6.16: Mean speed limit at the detector stations for the RCP algorithm.
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6.8 Conclusions

The VSL algorithms investigated and compared in this chapter have a main focus on traffic efficiency and traffic safety. The comparison shows that the design of, and the defined objective with, the algorithm have a great impact on the performance. It should be mentioned that the standard error of mean speed in some cases are too large to conclude a difference in performance between algorithms. This is of special importance when comparing the algorithms with results close to each other, i.e. the MCS, the SPECIALIST and the RCP algorithm.

The MTFC algorithm can be categorized as a harmonization algorithm while the MCS algorithm and the SPECIALIST algorithm can be categorized as incident detection algorithms. Both incident detection algorithms tend to have lower mean speed levels when the VSL signs are active compared to the harmonization algorithm. One reason for this is that the VSL signs included in the harmonization algorithm becomes active at an earlier stage, starting to prevent a breakdown before it actually occurs. While the VSL signs in the incident detection algorithms becomes active only when low speed conditions are detected and where the breakdown occur or is about to occur. This becomes clear when comparing the MTFC and the RCP algorithm, where the calculated speed limits for both algorithms are dependent on the conditions on the road. But even so the results from the algorithms are very different due to the distinctive objectives for lowering the speed limit.

For the incident detection algorithms it is also a matter of when the incident is detected. With a good incident detection the VSL signs becomes activated earlier and prevention of the breakdown can be made earlier as a result of that. For the SPECIALIST an earlier and more precise detection of the shockwave could potentially lead to a decreased application stretch resulting in higher mean speed. Also the duration for when the speed limits are lowered could be decreased, leading to a faster recovery rate towards the original speed limit on the road. The MCS algorithm have the same problem with the incident detection, but since the algorithm change from lower speed limits to the original speed limits as soon as the incident is not longer detectable the recovery rate is much faster than for the SPECIALIST algorithm. The ability to detect an incident is of cause also dependent on the distance between the detector stations. The time of detection of an incident occurring in between two detector
6.8. Conclusions

The RCP algorithm have a different strategy compared to the others. The algorithm can be categorized somewhere in between a harmonization algorithm and an incident detection algorithm since it is aiming at reducing high crash risk situations where incidents are likely to occur by harmonizing the flow. It is important to consider that by lowering the speed limits at some segments might result in high differences in mean speed between segments, counteracting the aim of the algorithm.

The focus for the RCP algorithm and the MCS algorithm is mainly on traffic safety. Although, for both algorithms a side effect of increasing traffic safety by preventing breakdowns are that the traffic flows are harmonized which potentially could lead to a more efficient traffic system. This is, however, not observable from the results presented here, where the lowering of speed limits seems to decrease efficiency measured as mean speed.

The objective of both the MCS and the SPECIALIST to prevent further incidents and smooth the traffic flow is reflected in the results, since the longer areas with lower speed limit results in less abrupt speed changes in space. The SPECIALIST algorithm does also serve its purpose to increase throughput at the bottleneck location where higher mean speed are observed compared to the base case.

It is important to notice that none of the algorithms can totally solve the problems related to congested situations, since vehicles cannot disappear. The performance of the algorithms are dependent on flow levels and the duration of the congested state. For example, for the MTFC, which is the algorithm that performs best with respect to mean speed, a higher inflow and a longer duration of high inflow would probably eventually cause a breakdown of the traffic system. This is a result of a too high inflow compared to what the traffic system can handle. Although, the algorithm is postponing the breakdown, and in some cases as is seen in this chapter even preventing a total breakdown.

A limitation for the MTFC and the RCP algorithms is that they both are applied to specific locations. Thereby the bottleneck location need to be known beforehand, while the MCS and the SPECIALIST algorithm can be applied for a long stretch and try to prevent breakdowns along the whole stretch.

The importance of choice of scenario used for modeling of congested situations does also need to be highlighted. In SUMO a rea-
sonable approach have been found which reflect reality well enough. The traffic system as a total is comparable with empirical studies over congested situations in a motorway environment. Although, the simulations shows that individual vehicles within the traffic flow sometimes behaves unexpectedly, for example the vehicles tend to have large speed differences between lanes.

Finally, in this chapter only reactive algorithms have been investigated and compared. Also many predictive algorithms exists in the literature, which have not been investigated here, and which might perform well and be of interest for actual implementation.
Chapter 7
Conclusions and future research

In this thesis, a cooperative variable speed limit system is proposed. The system is modeled and evaluated using microscopic traffic simulation. We have shown the potential benefits of incorporating infrastructure to vehicle communication and autonomous control to an existing variable speed limit system. Results from the evaluation indicate that a cooperative variable speed limit system can contribute to improvements related to traffic efficiency and environmental impacts.

One common limitation for many of the variable speed limit systems in operation is that the methods used to determine the speed limits are based on simple speed and/or flow thresholds. In the literature, more elaborate variable speed limit control strategies have been suggested. In this thesis, three of these strategies have been investigated and compared to a simple threshold based control algorithm. The aim of this study has been to quantify the resulting traffic performance of the control algorithms by the use of microscopic traffic simulation. The results show that the defined objective for the algorithms have a decisive influence on the effects of the variable speed limit system.

Also, the importance of choice of appropriate approach for modeling of merging behavior under congested situations within the microscopic traffic simulation tool SUMO have been examined and discussed.

We have identified a number of areas of interest for future research.
Chapter 7. Conclusions and future research

When designing a variable speed limit system incident detection, and especially the point in time when an incident is detected, has been shown to be important. By extending the cooperative variable speed limit system proposed in this thesis with vehicle to vehicle, and vehicle to infrastructure communication the incident detection could be further improved. In this case the vehicles in the traffic stream are used as probes for detection of incidents, instead of using fixed detector stations. Such communication could result in faster and more precise detection of congested traffic states and the cooperative variable speed limit system could be designed to adapt to both the variable speed limits on the road and to downstream vehicles. This would most probably enhance the performance of an incident detection based variable speed limit control algorithm.

The control algorithm used in the variable speed limit system are found to have a large impact on the performance of the system. We believe that a cooperative variable speed limit system like the system proposed in this thesis can be further improved by incorporation of a more sophisticated variable speed limit algorithm.

The control algorithm performing best with respect to traffic efficiency was the harmonization algorithm, MTFC. A limitation with such an algorithm is that the bottleneck location need to be known beforehand. If a harmonization algorithm could be integrated with active incident detection the control algorithm would become more flexible. In this case the bottleneck location along a road stretch is identified first when an incident is likely to occur, and the algorithm is applied to that specific location. Identification of the incident location can be done by using road detectors or by the use of vehicle to vehicle, and vehicle to infrastructure communication.

Therefore, in future research the aim is to (1) find methods for improving incident detection by making use of vehicle to vehicle and vehicle to infrastructure communication, (2) integrate cooperative system features with a more sophisticated variable speed limit control algorithm. The cooperative variable speed limit system could be based both on communication between vehicles, between vehicles and the infrastructure, and between infrastructure and vehicles, or a combination of them, and (3) combine a harmonization algorithm with incident detection.

Finally, the use of microscopic traffic simulation for evaluation of a cooperative variable speed limit system prior to implementation have been proven to be useful to give indications on the performance of
the traffic system, and the results from this thesis will be useful for further development of variable speed limit systems, both with respect to incorporating cooperative features and by improving the speed setting control algorithms. The results can also be used as a basis for investigations of other cooperative systems prior to implementation, similar to the ones presented in this thesis.


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ordination of variable speed limits to suppress shock waves.” In: 
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rithm based on shock wave theory.” In: 11th International IEEE 
Conference on Intelligent Transportation Systems. Beijing, China, 
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based variable speed limit control algorithm against jam waves - 
an extension of the SPECIALIST algorithm”. In: Proceedings 
of the 16th International IEEE Annual Conference on Intelligent 

on the safety and operational impacts of freeway variable speed 
limit systems.” In: Journal of Transportation Engineering 137(4), 
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Hoogendoorn, R., van Arem, B., and Hoogendoorn, S. (2013). “In-
corporating driver distraction in car-following models: Applying 
the TCI to the IDM”. In: Proceedings of the 16th International 
IEEE Annual Conference on Intelligent Transportation Systems 

multianticipative car-following behavior”. In: Transportation Re-
search Record 1965, pp. 112–120.


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Bibliography


Bibliography


Abbreviations

**ITS**  Intelligent Transport System

**VSL**  Variable Speed Limit

**C-VSL**  Cooperative Variable Speed Limit

**MCS**  Motorway Control System

**I2V**  Infrastructure to Vehicle

**V2I**  Vehicle to Infrastructure

**V2V**  Vehicle to Vehicle

**V2X**  Vehicle to Infrastructure or Vehicle

**CMEM**  Comprehensive Modal Emission Model

**SUMO**  Simulation of Urban MObility

**TraCI**  Traffic Control Interface

**MTFC**  Mainstream Traffic Flow Control

**SPECIALIST**  SP-Eed ControllIng ALgorIthm using Shockwave Theory

**RCP**  Reducing Crash Potential
Appendix A

Overview of projects

Table A.1: Projects on national and international level within Europe together with their main focus areas. The type of project refers to if the project is performed on national or international level, which is related to where the funding comes from. FP stands for Framework Programme.

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Chapter A. Overview of projects

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Chapter A. Overview of projects

Table A.6: Projects carried out in U.S. together with their main areas of interest. The type of project refers to if the project is performed on national or international level, which is related to where the funding comes from. OEM stands for Framework Original Equipment Manufacturer. US DOT stands for U.S. Department Of Transportation.

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<td>IntelliDriveSM (former VII)</td>
<td>US DOT</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>(IntelliDrive, 2009)</td>
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<tr>
<td>AERIS</td>
<td>US DOT</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<td>(IntelliDrive, 2009)</td>
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</tr>
<tr>
<td>CICAS</td>
<td>US DOT</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>(Minnesota Department of Transportation, 2009)</td>
<td></td>
<td></td>
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</table>
Table A.7: Projects carried out in Japan together with their main areas of interest. The type of project refers to if the project is performed on national or international level, which is related to where the funding comes from. OEM stands for Framework Orginal Equipment Manufacturer.

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>Application development</th>
<th>Technology</th>
<th>Test and evaluation</th>
<th>Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSVS (Gee, 1997)</td>
<td>governmental project</td>
<td>✓</td>
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<tr>
<td>AHSS (Gee, 1997)</td>
<td>governmental project</td>
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<tr>
<td>AHSRA (Gee, Schulze, 2006)</td>
<td>OEM project</td>
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<tr>
<td>Smartway (former AHSRA) (Schulze, 2006)</td>
<td>OEM project</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>ASV-I (IATSS Research, 2006; Wani, 2006; Gee, 1997)</td>
<td>governmental project</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>ASV-II (IATSS Research, 2006; Wani, 2006; Gee, 1997)</td>
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<td>✓</td>
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</tr>
<tr>
<td>ASV-III (IATSS Research, 2006; Wani, 2006)</td>
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<tr>
<td>ASV-IV (Wani, 2006)</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>VICS (VICS, 2010)</td>
<td>governmental project</td>
<td>✓</td>
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</tbody>
</table>
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