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Optimization of Ramp Metering Systems using Gap Detection and Cooperative Adaptive Cruise Control

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To my family and friends.

Success is not final; failure is not fatal: It is the courage to continue that counts.

Winston S. Churchill

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RESUMO

A gestão do tráfego está a tornar-se cada vez mais importante face, por um lado, à maior mobilidade e consequente aumento do volume de tráfego e, por outro, à limitação de espaço nas cidades densamente povoadas. Esta dissertação propõe a integração da deteção do intervalo de tempo entre veículos e do Sistema Cooperativo de Adaptação de Velocidade (CACC - Cooperative Adaptive Cruise Control) aplicado a um controlo de rampas de acesso a autoestradas urbanas (RMS - Ramp Metering System).

Para tal foi desenvolvido e avaliado um algoritmo de controlo tendo presente um cenário base sem qualquer tipo de controlo e sem a contribuição da componente CACC. O objetivo foi o de desenvolver uma estratégia que utilize a informação para otimizar o comportamento de convergência em rampas de acesso a autoestrada.

No teste de cenários foi adotada uma abordagem baseada na simulação para avaliar o desempenho da estratégia desenvolvida. Os resultados demonstram uma melhoria substancial em todos os indicadores de desempenho e, subsequentemente, no desempenho da rede, mas é necessária mais investigação para resolver as limitações deste estudo.

PALAVRAS CHAVE: GESTÃO E CONTROLO DE TRÁFEGO, SISTEMAS COOPERATIVOS E INTELIGENTES DE TRANSPORTES, SISTEMA COOPERATIVO DE ADAPTAÇÃO DE VELOCIDADE , CONTROLE DE RAMPAS DE ACESSO A AUTOESTRADAS, DETEÇÃO DE INTERVALOS DE TEMPO ENTRE VEÍCULOS.

ABSTRACT

Traffic management is becoming ever more important with the increasing mobility and the consequent impact in traffic flows and the limitation of space in densely populated cities. This dissertation proposes the integration of gap detection and Cooperative Adaptive Cruise Control (CACC) to a Ramp Metering System (RMS).

In this way, a control algorithm was developed and evaluated compared to a no control scenario, and RMS without the contribution of the CACC component. The objective was to develop a strategy that leverages real-time gap information to optimize merging behaviour.

A simulation-based approach was adopted to evaluate the performance of the developed strategy. The results demonstrate a substantial improvement in all key performance indicators and subsequently the network performance, but more research is needed to address the limitations of this study.

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LIST OF ACRONYMS

ITS   Intelligent Transport Systems

CAV   Connected and Automated Vehicle

CACC   Cooperative Adaptive Cruise Control

V2V   Vehicle-to-Vehicle

I2V   Infrastructure-to-Vehicle

RMS   Ramp Metering System

KPI   Key Performance Indicator

ACC   Adaptive Cruise Control

ICT   Information and Communication Technologies

C-ITS   Cooperative Intelligent Transport Systems

ALINEA   Asservissement Linéaire d'Entrée Autoroutière

ADAS   Advanced Driver Assistance Systems

DSRC   Dedicated Short-Range Communications

TMC   Traffic Management Centre

HGV   Heavy Goods Vehicle

KOV   Keep One Vehicle Gap

AOV   Allow One Vehicle in Front

VISSIM   Verkehr In Städten - SIMulationsmodell

COM   Component Object Model

MOO   Multi-Objective Optimization

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INTRODUCTION

Nowadays it can be stated that transport demand is rising and projections point to a growth of 40% in passenger demand and nearly 60% for freight between 2010 and 2050 (European Commission, 2016). In addition, building new infrastructure is becoming increasingly more difficult with space becoming a rare commodity in today's densely populated cities. In light of this, improving the efficiency of existing infrastructure becomes a vital target for futureproofing the road network.

In The Netherlands for example, initiatives like the "*Beter Benutten*" project aim at smarter use of existing infrastructure, smart mobility, and Intelligent Transport Systems (ITS) and has reported great success during the implementation phase between 2011 and 2017, leading to more than 48 000 hours of rush hour avoidances per working day (Rijkswaterstaat, n.d.). The country is also currently facing a persistent issue of traffic congestion in some of its major cities such as Amsterdam, Rotterdam, and The Hague. Rotterdam poses a significant challenge due to its position as the largest seaport in Europe and the resulting high volume of freight traffic. This has made it a priority for the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) to address the issue by initiating various projects, such as the construction of a new stretch of motorway to bypass one of the most critical bottlenecks, the Terbregseplein interchange (Rijkswaterstaat, 2023). Unfortunately, new construction is not feasible for all of the problematic areas, and so less intrusive methods need to be studied.

Traffic management and control has evolved to fight these issues with the introduction of systems like Ramp Metering Systems (RMS), Variable Speed Limits (VSL), and Variable Messaging Signs (VMS). While these technologies have been implemented with plenty of success, the future of transportation requires a more connected and cooperative approach to traffic management. For this purpose, new solutions are being developed and studied to get the best results out of the current road network. Connected and automated vehicles (CAVs) are one of those technologies and have the potential to be used in parallel with existing systems to improve traffic conditions by using a cooperative approach to traffic control. CAVs allow for more complex driver assistance systems like Cooperative Adaptive Cruise Control (CACC) which works by taking advantage of the Vehicle-to-Vehicle (V2V) capabilities to form platoons that drive at constant speed with a consistent headway distance between them (Wang et al., 2018). This homogenization of traffic flow might be coupled with existing traffic management and control systems to improve their performance.

There are multiple advantages of using CACC for traffic management. It can share position, acceleration, and speed data in a distributed network of CAVs that result in three main improvements. It improves traffic flow by homogenizing the speed within the platoon, reducing the likelihood of sudden braking or acceleration, thereby improving the traffic flow. However, potential traffic throughput benefits have only been observed for very high penetration rates (van Arem et al., 2006). CACC can also improve driver experience by reducing stress and frustration associated with heavy traffic, and finally, the reduced congestion and improved traffic flow can result in a decrease in travel time and subsequently a lower fuel consumption as well as harmful emissions (Shladover et al., 2015).

These advantages of CACC can be combined with successful existing roadside technologies to potentially compound on the performance improvements of both systems. Ramp metering systems, for example, have been used for over 30 years with various degrees of success, and have become a proven technology in traffic management and control to improve safety and throughput without the need for

expensive infrastructure projects and so have been the target of extensive research and development (Mizuta, 2014). Over the years, the control strategies for these systems have become exponentially more effective and complex (Shaaban et al., 2016), but efficiency could increase with better coordination with other ITS/C-ITS systems.

CAAC is an optimal candidate for RMS optimization, as the biggest problem in ramp metering is the merging aspect. Using a gap detection algorithm has been proven to produce a positive effect in RMS performance by coordinating the release of waiting ramp traffic when an available gap in motorway flow is available (Klomp et al., 2022). Using CACC to homogenize the gaps between vehicles can, in theory, make this approach more effective.

Multiple concepts using these technologies have been proposed, but there are not many who combine the improvements of in-vehicle technologies and the roadside equipment into a cooperative system. Studying the feasibility and performance of a integrated CACC and RMS system has, to the authors knowledge, not been done before. In line with this, this dissertation aims to evaluate this system for the A16 Rotterdam-Feijenoord on-ramp, which has been a persistent source of congestion. By examining the effectiveness of this strategy, the study seeks to contribute to the development of smarter and more effective solutions for traffic management.

Summing up, this chapter serves as an introduction to the problem under investigation. It outlines the nature of the problem, highlights its limitations, and establishes the research objectives. Furthermore, it contextualizes the relevance of the research in the field and provides an overview of the structure of the subsequent chapters.

1.1. PROBLEM DEFINITION

The current traffic management strategies employed in dense urban environments have not been able to effectively address the issue of traffic congestion. Despite multiple attempts at implementing various strategies, the efficiency gains have not kept up with the rising traffic demands. With expansion or new construction not being feasible, it has become imperative to find new solutions that incorporate emerging technologies to future-proof the traffic network management. Although autonomous vehicles have been considered as the ideal solution, their technology and public opinion are not yet ready. Therefore, an intermediate solution that leverages existing technology and can be adapted in the future is necessary.

RMS has proven itself a very successful roadside traffic management system, but the difficulties with the merging have caused a sub-optimal performance. CACC can be used for gap control, and with Infrastructure-to-Vehicle (I2V) and Vehicle-to-Vehicle communication capabilities, become a likely candidate for integration with RMS.

1.2. RESEARCH SCOPE

Given the extensive nature of the topics mentioned, limits need to be introduced to properly focus on the relevant research.

1.2.1. RMS OPTIMIZATION WITH CACC SYSTEMS

There are numerous ways of improving motorway throughput, from ITS/C-ITS systems to additional infrastructure, to modal measures. For the purpose of this dissertation, the focus will be on the elaboration of a control strategy using RMS, Gap Detection and CACC, as these systems have already been implemented or will be in the near future.

Two main variant types of CACC systems exist: V2V CACC and I2V-V2I CACC. The system this study will use is a combination of the two called Everything-to-Everything (X2X), as the two-way communication with roadside devices is essential for the suggested control strategy, and the communication between vehicles necessary for the management of the gaps. The system variants will be explained more in-depth in chapter two.

A standard communications protocol and standardized CACC module will be assumed to be implemented, as without communication between different brands the system will not be effective.

1.2.2. IDEAL CONDITIONS

Computational requirements for traffic management and control systems are assumed to be developed enough to allow for the real-time operation of these algorithms without significant delay. The human factor is not considered as well. Measures will be specified that discourage the overtaking behaviours of users into the created gaps, but this factor will not be considered.

Data privacy concerns of individual data collection and speed targeting will also not be considered, as that is beyond the scope of this research.

1.2.3. SIMPLE PROBLEM AREA/NETWORK

The focus of this dissertation will be at a single on-ramp location and will not take network-wide impacts into consideration. Further studies should be done to measure the consequences of such a control strategy on the complete network.

1.3. RESEARCH OBJECTIVES

This dissertation is motivated by the potential benefits described in the introduction of a cooperative strategy between RMS, Gap Detection and CACC.

The main objective of this dissertation is to identify/develop a control strategy to implement on existing ramp metering systems to optimize the performance of the motorway, using gap detection implemented with cooperative adaptive cruise control devices.

Two research questions were then formulated:

1. *How can a RMS control strategy that integrates gap detection and CACC be designed and implemented?*

2. *Would such a system be beneficial in terms of network performance?*

To answer these questions, several objectives were defined:

- To analyze existing techniques and strategies to regulate traffic output on motorways and their effectiveness;

- To develop a control strategy to optimize this outcome by incorporating RMS and Gap detection control strategies with CACC implementation;

- To evaluate the performance of the created strategy by comparison of Key Performance Indicators (KPIs);

- To design an optimization algorithm.

1.4. RELEVANCE

Adaptive cruise control systems (ACC) have existed for over 30 years and recently most auto manufacturers have been including a variation of the system in some of their new models, with Volvo, for example offering the system in all of their new models since 2015, and Tesla using ACC as a vital component in their autopilot technology. With the increased safety and environmental concerns of the last few years, systems that can provide substantial improvements to both factors while improving traffic conditions become very attractive to policy makers and consumers alike. The European Strategy on Cooperative Intelligent Transport Systems (C-ITS) and the Strategic Transport Research and Innovation Agenda (STRIA) have shown interest in the development and implementation of new connected technologies like CACC (Meyer et al., 2019). In 2018 the European Commission also released a mobility package that focusses on connected and automated driving that aims to reduce emissions, road fatalities and congestion (European Commission, 2018). There is also the EU Real-Time Traffic Information (RTTI) Directive, which states that traffic data should be publicly accessible in as close as possible to real-time for use of third parties (European Parliament, 2018).

Considering all this interest and investment in new connected technologies, it becomes relevant to study the effects of CACC in existing systems like RMS.

1.5. STRUCTURE

This study is composed of 5 chapters in total, including this first one that introduces the theme of this dissertation, the background of the work, identifies the research problem and defines the objectives and structure.

In chapter two the Literature Review/State-of-Art of the principal topics, namely ramp metering systems, gap detection and cooperative adaptive cruise control is presented. It also looks at existing control algorithms for controlling these systems. Finally, a summary of the literature and a discussion complete this chapter.

In chapter three the proposed control strategy, calibration and performance evaluation plan are described in detail.

Chapter four is the Case Study where the control algorithm is simulated for the Rotterdam-Feijenoord 24 ramp, and the results are presented and discussed. Then, the performance is evaluated on multiple key performance indicators.

In the fifth and final chapter are the conclusions of the dissertation and recommendations about future research and implementation of this technology.

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LITERATURE REVIEW

The objective of this chapter is to comprehensively examine current technologies, management and control strategies with the goal of identifying the most effective approaches for enhancing traffic conditions. In section 2.1, an introduction on the topics of RMS, Gap Detection and CACC is presented. In section 2.2, the research methodology is explained. The next 3 sections give information about what each of the three systems involved is, how they work, and what control strategies are relevant to know for the elaboration of the new algorithm. Sections 2.6 and 2.7 explains the cooperative control strategies that can be used to achieve better results. Finally, section 2.8 offers a comprehensive discussion and conclusion that encapsulates the entirety of the review.

2.1. INTRODUCTION

The traffic and transport engineering industry in the 21st century is facing a growing need for innovative solutions to improve traffic safety, reliability, and capacity. The International Transport Forum (ITF) predicts that non-urban transport will increase 2.5 times from 20,000 billion passenger kilometres in 2015 to 50,000 billion in 2050, highlighting the urgency for optimizing the existing transportation network (*ITF Transport Outlook 2017*, 2017). Congestion costs in Europe approximately represent 1% of its gross domestic product (GDP) annually, and both passenger and freight traffic are projected to rise significantly compared to 2005 levels (European Commission, 2011). Traffic engineers are experimenting with cost-effective new ideas and technologies to address these challenges.

Intelligent Transport Systems have been identified as a promising technology for overcoming current traffic issues. ITS integrate Information and Communication Technologies (ICT) to improve transportation management and services, collecting data from the road, vehicles, and users to enhance system performance, traffic safety, efficiency, and environmental impact reduction (Lin et al., 2017).

While the first generation of ITS was standalone and couldn't communicate with each other, a new generation of Cooperative Intelligent Transportation Systems allows for data-sharing and cooperation (Figure 1), which can extend the capabilities of traditional ITS and deliver even greater benefits (Greguric & Mandzuka, 2018). One promising technology within ITS is Cooperative Adaptive Cruise Control, which has been researched primarily for its safety benefits. However, this technology can also help stabilize and homogenize traffic flow, which can work in conjunction with other traffic-controlling measures like Ramp Metering Systems or Gap Detection algorithms to improve traffic performance and decrease congestion.
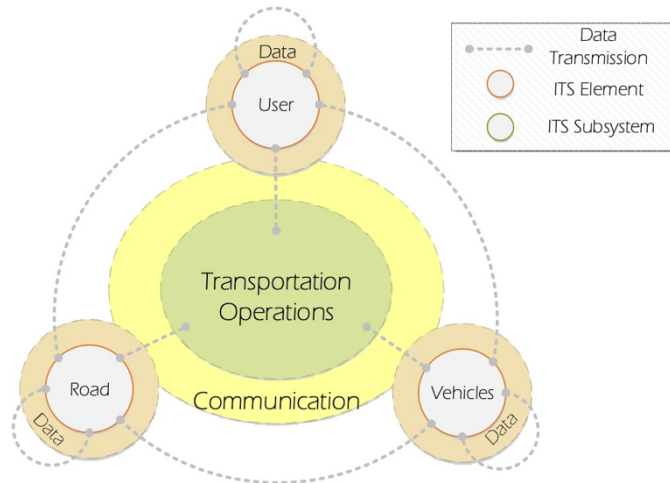
Figure 1: ITS interconnection (Lin et al., 2017)

2.2. METHODOLOGY

This literature review was elaborated to evaluate the feasibility of a cooperative control strategy of RMS, Gap Detection and CACC. For that purpose, both systems and gap detection methods were researched, and the cooperation possibilities investigated.

The search strategy involved the use of regular search engines (Google Scholar) and several online databases (Scopus, IEEExplore, TUDelft Repository) with the following keywords: "Ramp Metering Systems (RMS)", "Cooperative Adaptive Cruise Control (CACC)", "Gap Detection", "Traffic Management", "Congestion". The research was limited to English language peer reviewed articles, published within the range of 2000 until 2022, and selected if they met the following criteria:

1. Included any/multiple of the aforementioned traffic management systems;
2. Were based on the cooperation of ITS systems;
3. Focussed on congestion management in motorways;
4. Written by proven experts in the field of traffic management;
5. Written in English.

This resulted in 4 articles on CACC, 11 articles on RMS, and 3 articles on ITS. Articles can be consulted in the references. The quality of the articles was evaluated by indicators like number of citations, where it was published and the authors contributions to the field. A summary of the articles studied for this dissertation can be found in Table 1.

Given the nature of the research, some limitations on the sample size of relevant research, language of the study, and the absence of existing research on this specific topic were noted.

Table 1: Summary of articles

Author, Year	Subject	Focus of the Study	Conclusions
Shladover et al., 2015	CACC	Definitions and Concepts of CACC.	CACC has potential to improve traffic performance, although more research is needed.
Milanes et al., 2014	CACC	Implementation of CACC in real traffic scenarios.	CACC showed improvements in response time and string stability, indicating a possible improvement in highway capacity and traffic flow stability.
van Arem et al., 2006	CACC	Impact of CACC in traffic flow characteristics.	CACC shows potential positive benefits on traffic throughput and stability. These results are shown for a high penetration rate, with low penetrations leading to a decrease in performance.
Wang et al., 2018	CACC	CACC architectures, controls and applications.	While many studies on CACC have already been done several questions remain: High cost, need for more reliable architecture and a ready-to-market control methodology.
Taale, 2000	RMS	Evolution of RMS in The Netherlands.	RMS is successful in The Netherlands and performance gains have been proven, though performance evaluations vary in their methods. A general evaluation framework should be developed.
Chu et al., 2004	RMS	Performance evaluation of RMS control algorithms using a microscopic model.	Adaptive RMS has performance advantages compared to fixed-time control. The strategy studied is reactive but proactive control is desired.
W. Jin & Zhang, 2001	RMS	Review of RMS algorithms and development of an evaluation framework.	RMS appears to be more effective in certain demand scenarios. Parameter tuning is essential for good performance. All algorithms perform similarly with a general travel time reduction.
Middelham & Taale, 2006	RMS	Review of RMS in The Netherlands	Similar conclusions to (Taale, 2000)

Table 2: Summary of articles (Cont.)

Shaaban et al., 2016	RMS	Advancements in adaptive RMS.	ALINEA eliminates downstream congestion, but it cannot detect it when it starts upstream. Local RMS strategies depend on the storage capacity of the on-ramp. Fuzzy logic algorithms have great potential but require more input data than other methods.
Xu Yang et al., n.d.	RMS	Genetic algorithm optimization of ALINEA parameters.	GA optimization creates positive effects. The RM update rate needs to be carefully studied. If updates are too quick it can lead to turbulence in the mainline traffic, and if too slow the RMS cannot respond in time to changing traffic conditions.
Mizuta, 2014	RMS	RMS overview, challenges, and implementation guideline.	The successful implementation of RMS requires careful planning of infrastructure and control algorithms, and some locations are not suited for RMS.
Klomp et al., 2022	RMS	RMS with microscopic gap detection.	The algorithm has performance gains compared with both the reference macroscopic algorithm and the base scenario. The benefit is more noticeable in high flow, with the effect lessening as it gets closer to the activation flow. More studies need to be done to optimize this strategy.
van de Weg, 2013	RMS	Cooperative RMS with variable speed limits (VSL).	Strategy has resulted in an improvement in traffic throughput. Ideal conditions were considered so further research needs to be done to quantify realistic performance.
Tian, 2004	RMS	RMS strategy for integrated diamond interchange.	Variable metering rates more effective, queue flush strategy caused earlier traffic flow breakdown.
Trubia et al., 2021	RMS	RMS evolution and evaluation of recent developments in control algorithms.	Advancements in technology make more complex algorithms possible. Existing models need to evolve, and development of connected vehicles bring exiting possibilities for traffic management.

Table 3: Summary of articles (Cont.)

Lin et al., 2017	ITS	Development of an ITS architecture based on existing and future developments.	Opportunities for ITS system improvements lie in CAVs, microscopic vehicle coordination, and improving the simulation models with access to more data.
Greguric & Mandzuka, 2018	ITS	ITS control using Intelligent Speed Adaptation (ISA)	ISA can provide a solution to non-compliance to speed limits. The technology shows potential not only for safety benefits but also traffic congestion and efficiency improvements.
P. J. Jin et al., 2017	ITS	Active traffic management using gap metring.	Gap metering has potential for reducing traffic congestion and can help improve the performance of existing ITS systems, and RMS in particular.

2.3. RAMP METERING SYSTEMS (RMS)

In situations with high traffic volume, accessing the motorway can be challenging for users as merging becomes increasingly difficult. Multiple vehicles attempt to enter the motorway in tight platoons, resulting in a queue at the merging section, or a forced entry into the mainstream which can cause a shockwave as cars in the mainline have to slow down to prevent an accident (Taale, 2000).

To address this issue, Ramp Metering Systems are used to regulate the number of vehicles entering a motorway using traffic lights. These systems limit the flow of incoming traffic, which can quickly resolve bottlenecks or prevent congestion altogether by managing the capacity drop phenomenon. They also break up platoons that can cause disruptions when merging all at once, by releasing vehicles at certain rates to optimize traffic flow (Middelham & Taale, 2006).

In this section it will be explained how the system works, what are the typical design elements, the effects of RMS on the most common indicators, and finally a review of the relevant control strategies will be performed.

2.3.1. RAMP METERING SYSTEMS

In an RMS the loop detector data of a section of the motorway is transmitted to a controller, which compares it to predetermined threshold values. If these values are "exceeded" (less than a fixed gap), the system is initiated, and the metering signal is activated. The system then follows a control strategy to adjust the signal timings to regulate the entry flow of the merging ramp. Typically, the system allows for a single vehicle or a small platoon of vehicles per green cycle, while the red cycle is adjusted based on the conditions of the motorway and the on-ramp. Additionally, ramp queue detectors provide valuable information to the controller, which decides if it needs to flush out the ramp traffic to avoid overspilling onto local roads (Taale, 2000).

By incorporating loop and queue detectors, along with a controller and metering signal, it becomes possible to effectively manage traffic flow, thus preventing congestion and enhancing safety measures.

This system can be easily adapted to suit a variety of on-ramp and motorway conditions, ensuring optimal flow management.

2.3.2. RMS DESIGN ELEMENTS

The design elements of RMS are typically categorized into two groups: motorway systems and on-ramp systems, as illustrated in Figure 2 and described after.
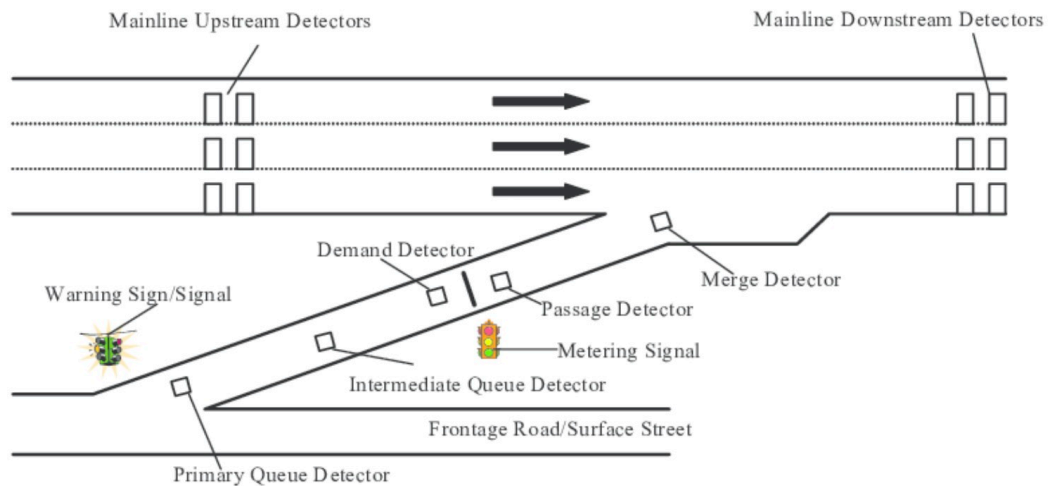
Figure 2: Typical RMS configuration (Tian, 2004)

The motorway systems consist of the following elements:

1. Mainline Upstream Detectors to provide information about incoming traffic;

2. Mainline Downstream Detectors to provide information about outgoing traffic (the incoming traffic plus the merging traffic), playing a crucial role in measuring the impact of the merging vehicles on the traffic flow.

On-ramp systems include the following components:

1. Metering signal (signal head): this traffic signal operates on either a green-red cycle or a green-yellow-red cycle depending on the presence of the yellow light;

2. Demand detectors to inform the system about the presence of waiting traffic on the on-ramp;

3. Passage detectors to inform the system about the vehicles that have passed through the metering signal;

4. Queue detectors also called advanced warning devices, used to detect incoming demand and queue formation;

5. Road signage placed at the beginning of the ramp and near the signal head to provide information to drivers.

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2.3.3. CONTROL STRATEGIES

There are various degrees of complexity in the control strategies of RMS, ranging from static to adaptive based on real-time traffic conditions (Shaaban et al., 2016; Trubia et al., 2021). These strategies include:

- Fixed Time/Rates: In this approach, the rates are pre-set based on a predetermined schedule or historical data. This method is simple and inexpensive to implement, requiring minimal equipment, and is effective for recurring congestion. However, it does not consider real-time traffic measurements and is not effective for other types of congestion;

- Traffic Responsive/Adaptive: Rates are calculated by algorithms or pre-set matrixes using real-time traffic data. This strategy is more flexible than fixed time/rates and can adjust to changes in traffic conditions. However this strategy can only occur during specific time intervals due to policy or management reasons;

- Local Control: This is a type of traffic-responsive strategy that focuses only on a specific location and does not consider other nearby ramps or RMS;

- System-Wide Control: This is a coordinated approach to traffic adaptive control that adjusts based on a network of ramps or in cooperation with other ramp metering systems.

These systems are often implemented together to provide backup in case of malfunctions. A coordinated approach to ramp metering is best for network optimization, but is more expensive than local, simple systems. Table 4 presents the advantages and disadvantages of each strategy.

Table 4: Advantages and disadvantages of control strategies

Control Strategy	Advantages	Disadvantages
Fixed Time/Rates	Cheap and easy implementation. No detectors needed.	Static system, nonadaptive to irregular scenarios; Requires periodic manual updates.
Traffic Responsive/Adaptive	Flexible; Can adjust to changes in traffic conditions.	Can only occur during specific time intervals.
Local Control	Traffic responsive, self-regulating. Lower operational costs compared to fixed rate systems.	Locally focussed; More infrastructure is needed (detectors).
System-Wide Control	Cooperative; Good for network-wide traffic optimization.	Expensive to implement and maintain.

Overall, adaptive ramp metering strategies based on real-time traffic data are more effective in reducing congestion and improving traffic flow. However, these approaches require more equipment and higher initial investment. The choice of the optimal ramp metering strategy depends on factors such as traffic patterns, road infrastructure, and budget.

2.3.4. EFFECTS OF RAMP METERING

Extensive research has been conducted over the years on RMS. In the Netherlands, a series of studies have specifically examined the effects of ramp metering, assessing its impact by analyzing the most prevalent indicators. The findings of these studies are summarized in Table 5.

Table 5: Effects of Ramp Metering (Taale, 2000)

	capacity bottleneck	speed motorway	use of on-ramp	total delay (veh.hours)	travel time motorway	ignoring red light
Coentunnel (1 on-ramp)	=	+30 km/u	-50%	-	-	5-6%
Coentunnel (4 on-ramps)	+1-2%	+20 km/u	≈	-20%	-	-
Delft-Zuid (1st assessment)	+5%	-	=	<	-	15%
Delft-Zuid (2nd assessment)	+4%	-	=	<	-	15%
Zoetermeer	+3%	-	=	-	-6%	13%
Schiedam-Noord	>	+20 km/u	-8%	-	-6%	3%
Barendrecht	+5%	+20 km/u	-35%	-	-10%	2%
Kolkweg	=	+4 km/u	-10%	-	-3%	6%
Vianen	+5%	+5 km/u	-36%	-	-	5%
Muiden/Muiderslot	-	-	≈	-	=	6-7%

'=' means equal, '<' means decrease, '>' means increase, '≈'means variable and '-' means not studied

The impact of RMS on traffic flow has been analysed through several studies, but capacity effects were inconsistent, averaging around 3-5%. Motorway speed showed improvement in all studies, but the degree of improvement varied significantly - some studies reported less than a 10 km/h increase, while others saw improvements of over 20 km/h. It is also important to examine the use of on-ramps, as RMS can discourage "rat-runners". The results of these studies showed a general decrease in on-ramp use, with varying levels of impact depending on user options. Total delay was not widely studied, and total travel time consistently decreased by 3-10%. Acceptability of the system was also analysed in almost all studies, with the rate of drivers ignoring the red light ranging from 5-15%, depending on the bottleneck, but decreasing to 2-3% with the installation of a camera (Taale, 2000).

Overall, while the effects of RMS on capacity were inconsistent, improvements in motorway speed and reduced on-ramp use were consistently observed. Additionally, the studies showed a decrease in total travel time and generally acceptable levels of user compliance.

2.3.5. ASSERVISSEMENT LINÉAIRE D'ENTRÉE AUTOROUTIÈRE (ALINEA)

ALINEA is a reactive feedback control ramp metering algorithm that has become one of the most popular systems in use today. Designed for implementation on a single ramp at a time, ALINEA uses occupancy data and past-time metering rates to maintain a desired occupancy on the downstream mainline motorway (Xu Yang et al., n.d.). Field tests of the ALINEA algorithm have demonstrated that it is a cost-effective and highly efficient system, even when compared to more complex coordinated algorithms like METALINE (Chu et al., 2004; Jin & Zhang, 2001). The primary objective of ALINEA is to regulate the metering rate to ensure that traffic flow stays within motorway capacity limits. However, one limitation of this algorithm is that it can cause long ramp queues, leading to bottlenecks that may reduce performance. This issue can be mitigated by ensuring that there is sufficient ramp length to store the traffic (Shaaban et al., 2016)

Overall, ALINEA is a reliable, efficient, and cost-effective ramp metering algorithm that provides a reactive feedback control system for regulating traffic flow. While it may create long ramp queues that cause bottlenecks, this issue can be managed through proper planning and infrastructure design.

2.3.6. METALINE

METALINE is a reactive algorithm that was developed as an extension of ALINEA for coordinated applications, specifically designed for multiple on-ramp control. The algorithm operates in a similar manner to ALINEA but takes data input from multiple on-ramps. However, the calibration of METALINE is more challenging compared to local algorithms, as noted by Shaaban et al., (2016).

While METALINE has limitations in terms of calibration, it still presents a promising solution for controlling traffic flow on multi-on-ramp motorways. The algorithm's ability to coordinate data inputs from multiple sources could lead to significant improvements in traffic efficiency and overall road network performance. Nevertheless, further research is needed to address the calibration challenges and fully explore the potential of this algorithm.

2.3.7. MACRO AND MICROSCOPIC RAMP METERING STRATEGIES

Currently implemented RMS algorithms are of a macroscopic nature (Klomp et al., 2022). They usually work by reducing the on-ramp motorway inflow to prevent congestion, using aggregate data like flow, average speed and occupancy. By reducing the inflow, they reduce the probability of a vehicle not having a gap to merge into the mainstream, and so minimize congestion. It is still possible that this strategy leads to a traffic breakdown as the RMS releases a vehicle without knowing if it has a gap to merge into smoothly. If the vehicle cannot merge smoothly, it will have to force its way into the mainstream flow, which can cause congestion upstream.

Unlike macroscopic strategies, microscopic techniques search for gaps in the mainstream traffic flow to allow for improved merging performance. By controlling individual vehicles, the ramp metering can be optimized. This topic has been extensively researched, and while a general consensus is of a significant increase in performance, it is dependent on the penetration rates of CAVs, as most studies assume a 100% rate while others show benefits for a rate of at least 50% (Klomp et al., 2022).

Some strategies are being developed that use microscopic strategies to improve the performance of existing traffic management strategies. Gap detection is a microscopic strategy based on using individual car detection to improve on-ramp performance. This strategy has potential to be used with RMS to help prevent merging conflicts. Section 2.4 will explain this concept in more detail.

2.4. MICROSCOPIC GAP DETECTION

Microscopic gap detection is a traffic management technique that aims to improve safety and efficiency on roads by accurately measuring the distance between vehicles in traffic. It involves the use of sensors and other technologies to detect the gaps between individual vehicles. This information can be used by traffic management systems to make decisions about traffic flow, such as adjusting traffic signal timing or controlling access to motorways.

One key application of microscopic gap detection is the development of connected and autonomous vehicles (CAVs). These vehicles rely on accurate information about the position and movement of nearby vehicles to operate safely and efficiently (Klomp et al., 2022). Using information about microscopic gaps, CAVs can better understand their surroundings and make more informed decisions about acceleration, braking, and lane changes.

This section will explore the topic of gap metering, how it works, and how it can be used to improve the performance of ramp metering.

Gap metering is a traffic management technique used on motorways to improve traffic flow and reduce congestion. It can be thought of as a non-stop ramp metering where vehicles are controlled on the mainline to guarantee gaps for entering vehicles, ensuring efficient and smooth merging.

To implement gap metering, traffic signals are used to advise drivers upstream to maintain gaps between them to ensure homogenous and predictable gaps to improve the performance of the merging section. This can be achieved by traffic signs (Figure 3).
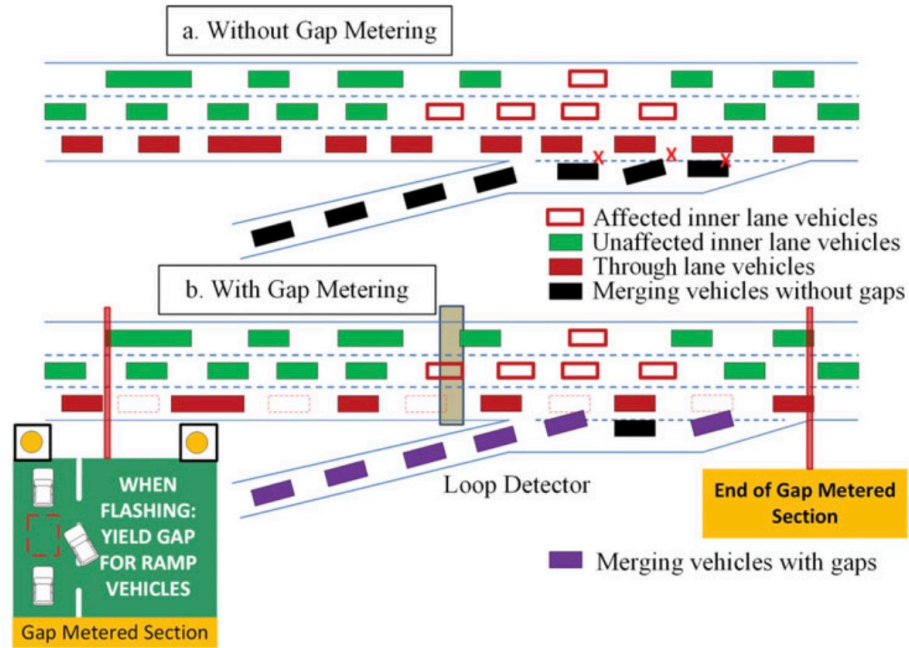
Figure 3: Gap metering using traffic signs (P. J. Jin et al., 2017)

Other ITC technologies can be combined with gap metering for better results. For example, ramp metering may be installed at the on-ramp to regulate the flow of vehicles onto the highway, or variable speed limit signs may be used to slow down traffic on the highway and create larger gaps between vehicles (P. J. Jin et al., 2017).

By regulating the flow of vehicles onto the highway in this way, gap metering can help to maintain a safe and efficient flow of traffic and reduce congestion. This strategy can be combined with RMS to control the ramp traffic, improving the merging performance (Figure 4). To ensure compliance, radar or video systems can be installed coupled with displays that inform the drivers of their current gap (P. J. Jin et al., 2017).

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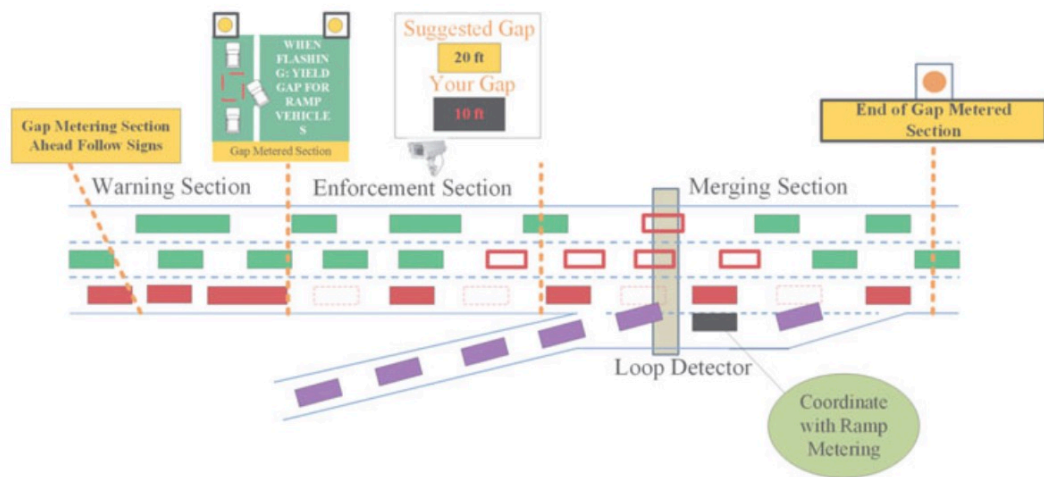
Figure 4: Advanced gap metering system design (P. J. Jin et al., 2017)

This strategy has the potential to be improved using more advanced technologies. Advanced Driver Assistance Systems (ADAS) can be used like ACC or CACC to help drivers maintain the gap safely and effectively ensuring a more comfortable experience with the system.

2.5. COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC)

Cooperative Adaptive Cruise Control is an advanced driver assistance technology that uses wireless communication between vehicles (V2V) or with infrastructure (I2V) to improve traffic flow and reduce congestion. CACC builds on conventional Adaptive Cruise Control technology, which uses radar or other sensors to maintain a safe distance between a vehicle and the vehicle in front of it.

In V2V CACC, vehicles communicate wirelessly with each other to share information about their speed, position, and other parameters. This allows vehicles to operate in a platoon, with each vehicle following closely behind the vehicle in front of it while maintaining a safe distance. The lead vehicle in the platoon controls the speed of the group, while the following vehicles adjust their speed and position to maintain a safe gap (Shladover et al., 2015).

CACC can provide several benefits over conventional ACC, including improved traffic flow, reduced congestion, and increased fuel efficiency. By allowing vehicles to travel more closely together, CACC can reduce the space needed between vehicles and increase the capacity of roads and motorways. It can also reduce the frequency and severity of braking and acceleration events, which can help to reduce fuel consumption and emissions (Milanes et al., 2014).

However, there are also a few challenges associated with CACC that need to be addressed before it can be widely adopted. These include the need for standardized communication protocols between vehicles, the development of robust cybersecurity measures, and the need for driver education and training to ensure that drivers are comfortable with the technology and understand how to use it safely.

In this part of the chapter, it will be explained how the system works, the types of CACC systems, and how we can integrate it with gap detection.

2.5.1. HOW CACC WORKS

Cooperative adaptive cruise control works by using wireless communication between vehicles to coordinate their movements and maintain safe distances between them (Figure 5). CACC systems use dedicated short-range communications (DSRC) or cellular technology to allow vehicles to exchange information with each other in real-time (Milanes et al., 2014).
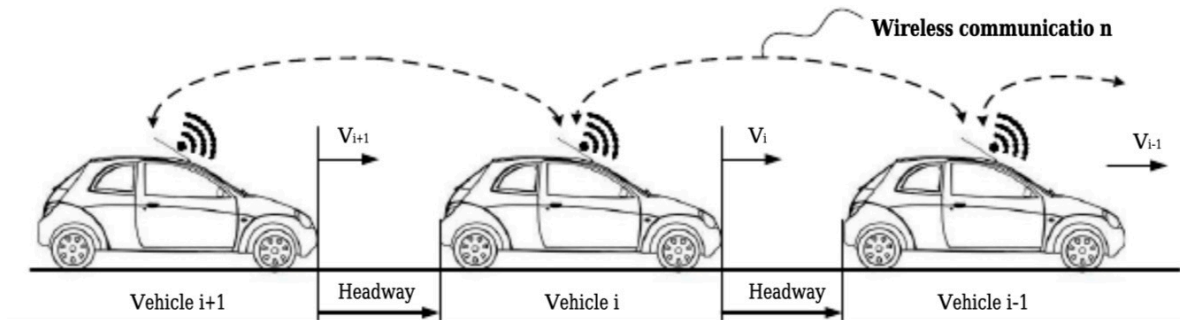
Figure 5: V2V Cooperative Adaptive Cruise Control (Wu & Zhu, 2021)

CACC systems can use a variety of sensors to gather information about the environment, including radar, lidar, and cameras. They can also use GPS and map data to anticipate changes in the road ahead and adjust the speed and position of the platoon accordingly (Shladover et al., 2015).

When a vehicle equipped with CACC approaches another vehicle, it uses its sensors to detect the position and speed of the vehicle in front of it. It then communicates this information to the following vehicles in the platoon using V2V communication, which use it to adjust their speed and maintain a safe distance behind the lead vehicle. The lead vehicle controls the speed, and the following vehicles automatically adjust their speed and position to maintain a safe gap. More advanced CACC systems can even get information from vehicles beyond the line of sight (Shladover et al., 2015).

2.5.2. TYPES OF CACC SYSTEMS

There are two main types of CACC variants: Vehicle-to-Vehicle and Infrastructure-to-Vehicle.

V2V CACC systems are dependent on frequent information updates and communication reliability to be effective. The data transferred within the network should include at least speed, location, acceleration and deceleration, intentions, and performance limitations (Shladover et al., 2015). In simpler systems the V2V communication is done from one vehicle to the next immediate predecessor. This has a big disadvantage in that the communication delays can accumulate down the chain. More advanced systems communicate with multiple vehicles at once, eliminating most of the delay.

I2V CACC systems can communicate with the Traffic Management Centre (TMC) allowing for instructions and recommendations to be given to the individual vehicles according to the control strategy in use. This information can be static or dynamic. Static data is information that is not subject to change often like posted speed limits, and dynamic data is information that is time-sensitive like variable speed limits or changes in traffic conditions (Shladover et al., 2015).

A combination of these systems will be the focus of this research as the ability to communicate with other vehicles and the roadside systems make it a promising candidate for RMS integration with gap detection.

2.6. CACC INTEGRATION WITH GAP DETECTION

Integrating CACC with gap detection algorithms has the possibility to help make gaps more uniform and improve ramp metering performance.

Traditionally, gap metering algorithms rely on fixed time intervals or predefined gaps to regulate the flow of traffic (P. J. Jin et al., 2017). However, this approach can result in uneven gaps and cause congestion, especially during peak traffic periods. By integrating CACC with gap detection algorithms, vehicles can communicate with each other to maintain a more uniform gap distance and adjust their speed accordingly.

CACC can use vehicle-to-vehicle communication to enable vehicles to coordinate their movements and maintain a consistent gap between each other. When a lead vehicle applies the brakes, CACC-equipped following vehicles will receive a signal indicating the deceleration rate and can adjust their speed accordingly to maintain the required headway gap (Shladover et al., 2015). This can help to reduce the fluctuations in gap distances and improve the accuracy and predictability of gap detection.

Furthermore, the traffic management controller can give instructions to vehicles equipped with this technology on when to extend or reduce the headway distance of the platoon, granting a more effective management of the traffic flow in high-demand or congested situations (Shladover et al., 2015).

2.7. RMS INTEGRATION WITH CACC

Coordinated control strategies for Ramp Metering Systems and CACC integration has the potential to improve traffic flow and reduce congestion on motorways.

Ramp metering systems regulate the flow of traffic by controlling the number of vehicles entering the highway at on-ramps. By limiting the number of vehicles entering the highway, ramp metering systems can prevent the occurrence of congestion and improve travel times. However, ramp metering can also create delays for vehicles waiting to enter the highway.

CACC can work in conjunction with ramp metering systems to help reduce the delays caused by ramp metering. Coordinated control strategies for ramp metering systems and CACC integration involve using V2V communication to provide CACC-equipped vehicles with real-time information on ramp metering rates and traffic conditions. CACC-equipped vehicles can then adjust their speed and position accordingly to minimize the impact of ramp metering on traffic flow.

In summary, coordinated control strategies for ramp metering and CACC integration involve using V2V and I2V communication to provide CACC-equipped vehicles with real-time information and instructions. By adjusting their speed and position accordingly, CACC-equipped vehicles can help to minimize the impact of ramp metering on traffic flow and reduce congestion on motorways.

2.8. CONCLUSION

As traffic demands continue to increase, traditional traffic management techniques are struggling to keep up. This presents a significant challenge for traffic engineers, who must consider factors such as budget, space limitations, and environmental impacts when designing solutions. To address these challenges, researchers are investigating innovative approaches that can integrate different intelligent transportation systems into traffic control strategies.

This literature review explores the possibilities of using a cooperative system of ITS, which includes ramp metering systems, gap detection, and cooperative adaptive cruise control. When combined, these systems have the potential to provide better performance than standalone applications.

The main focus of this dissertation is to propose a strategy that uses a combination of RMS, Gap detection and CACC to create gaps in traffic for RMS to release traffic and ensure the best motorway performance possible. The headway distances of individual road users are dynamically adapted using a control algorithm and implemented by CACC, which is controlled by the RMS control strategy.

In conclusion, a cooperative system of ITS, which includes RMS, Gap Detection and CACC, has the potential to improve traffic flow, reduce accidents, and enhance overall transportation system performance. While there are limitations to be solved before implementation, optimizing the integration of these systems can provide a more efficient and effective solution to the challenges faced by traffic engineers.

3
CONTROL STRATEGY

This chapter features the technologies and techniques explained in chapter two into a control strategy. Therefore, achieving the second research objective outlined in the introduction. In the next chapter, the results of the control algorithm are measured using a case study. The control strategy is based on the paper by Klomp et al., (2022).

3.1. INTRODUCTION

A control strategy or algorithm is a set of step-by-step instructions for solving a problem or performing a task. In this case, the objective of the algorithm is to maximize certain parameters that will be explained further in this chapter. It consists of several components:

1. Input: This is the information or data that the algorithm will use to solve the problem. For the purposes of this study, the input data will be motorway traffic speeds, traffic flow, position, ramp metering rate and ramp queue length. This data will be collected by loop detectors on the motorway and on-ramp, and the RMS controller.

2. Output: This is the result or solution that the algorithm produces after processing the input data. The output will be in the form of ramp metering rates and CACC instructions.

3. Variables: These are the values or data that are used in the algorithm. The variables in this control strategy will be average speed and flow thresholds, activation time, margin, queue time limit, and the gaps from the detectors to the merging section for the vehicle types.

4. Operators: These are the symbols or functions that are used to manipulate the variables in the algorithm. Examples of operators used in this algorithm are arithmetic operators (e.g. addition, subtraction), logical operators (e.g. AND, OR), and comparison operators (e.g. greater than, less than).

5. Control structures: These are the structures that control the flow of the algorithm. Some control structures used for the control strategy include loops (which repeat a set of instructions), conditional statements (which make decisions based on the value of a variable), and subroutines (which allow the algorithm to call other algorithms).

6. Termination condition: This is the condition that determines when the algorithm should stop processing. For this example, the termination conditions are based on traffic speeds, traffic flow and ramp queue length.

Figure 6 illustrates the control strategy's structure, depicting the various control modules alongside the input and output data.
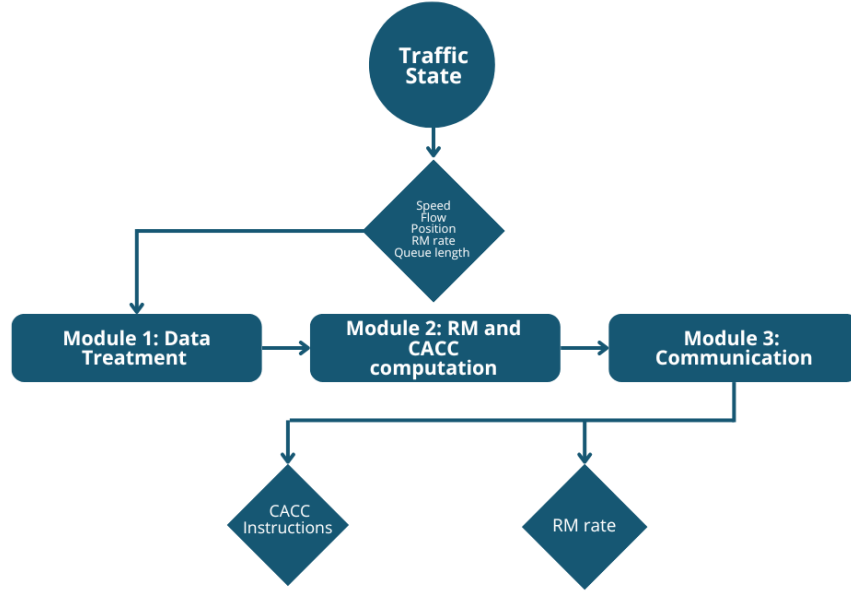
Figure 6: Control System Structure

3.2. METHODOLOGY

After the different systems are explained, a control strategy is developed based on previous studies using RMS in cooperation with gap detection and knowledge of CACC operation. The study done by Klomp et al., (2022), uses a logic algorithm that controls RM rates by means of gap detection. This algorithm was used as inspiration and modified to include the CACC component.

The required infrastructure and layout are determined by system requirements and the local regulations in place, and the activation and deactivation requirements are chosen based on traffic flow theory and assumptions of the effectiveness range of the strategy. Acceleration profiles have also been considered and adjusted according to the model calibration phase, for this, the assumptions and calibration variables were defined. Lastly, a performance evaluation plan was outlined and KPIs chosen.

3.3. NETWORK LAYOUT

The placement of the required infrastructure is an extremely important step in the implementation of the strategy. Sufficient time needs to be guaranteed to detect the mainline flow, to allow for the computation of the algorithm, and the acceleration of the vehicles to the merge zone with sufficient time and speed. Local regulations also need to be considered. Based on the site geometry, the local design standards, and the vehicle dynamics the optimal position for the detectors and RMS can be calculated.

The required infrastructure is described in Table 6 and the corresponding graphical representation in Figure 7.

Table 6: Detector Descriptions and Locations

Ref. Number	Detector Type	Description	Location	Veh. Type Detection
1	Congestion Measurement	Congestion detection downstream of the merging area. Deactivation of the control system depends on data from this detector.	On the right lane of the motorway, 275 m downstream of start of the merging section.	No
2	Red Detection	Verifying that the vehicle has crossed the stop line sufficiently. When activated, turns the traffic signal red.	One vehicle length downstream of the stop line after the yellow detection (Approx. 4 m).	No
3	Yellow Detection	Verifying that the front of the vehicle has crossed the stop line sufficiently. When activated, turns the traffic signal yellow.	Half a vehicle length downstream of the stop line (Approx 2 m).	No
4	Demand Detection	Detects waiting traffic at the stop line.	Approx. 2 m upstream of the stop line.	Yes
4L	Intermediate Queue Detection	Checks if a vehicle is approaching the stop line or if multiple vehicles are waiting. Can also be used for vehicle type detection. This detector will not be implemented in simulation.	Upstream of the stop line before detector 4.	No
5	Queue Detection	Detects queue formation on the on-ramp. The placement of this detector is a balance between queue storage capacity and ramp discharge.	Near the start of the on-ramp (115 m upstream of the stop line).	No
6	Traffic Measurement	Traffic data measurements. The activation of the system is determined by this detector by comparison with predetermined threshold values.	280 m upstream of the beginning of the merging section on the mainline.	No
7	Gap Detection	Gap detection and vehicle type identification. The vehicles on the on-ramp get released depending on the measurements of this detector. If the detector is not triggered for a certain amount of time the RMS will turn green.	450 m upstream of the beginning of the merging section on the mainline, before detector 6.	Yes
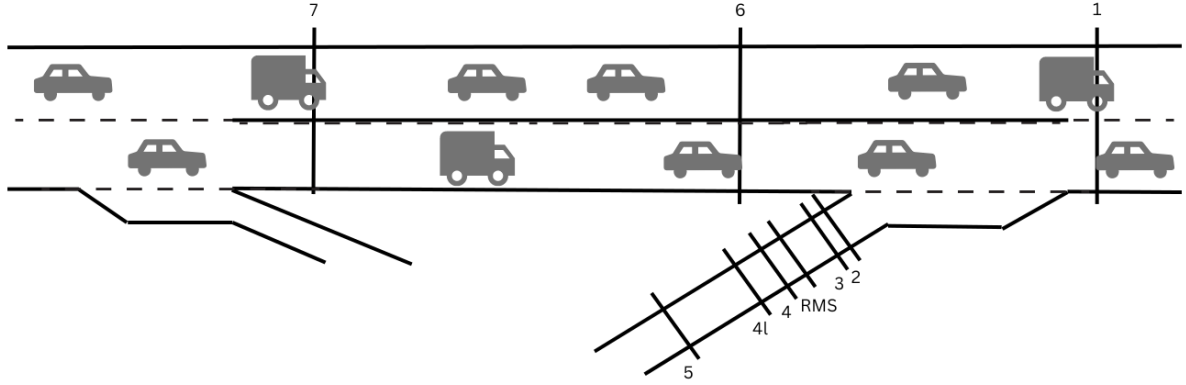
Figure 7: Network Layout

3.4. MICROSCOPIC RAMP METERING ALGORITHM

The objective of the algorithm is to improve RMS performance using a microscopic traffic control approach. This approach is beneficial as the current RMS performance is not good enough and has issues in certain scenarios. In this section, the working of the algorithm is presented, including the activation and deactivation conditions.

To trigger the system, flow and speed thresholds were established to be assessed at the first mainstream detector upstream of the merging section (traffic measurement detector). The system will activate if either the flow surpasses the lower threshold or if the average speed falls below the upper threshold, as these may indicate distinct types of congestion. The system will deactivate if either the flow falls below the lower threshold or if the average speed increases above the upper threshold, as these conditions indicate a stable uncongested state. The system will also deactivate if the speed falls below the lower threshold, as these conditions are heavily congested, and so the system has no positive impact. The fundamental diagram of traffic flow (Figure 8) can be used to illustrate the operational zone of the system.
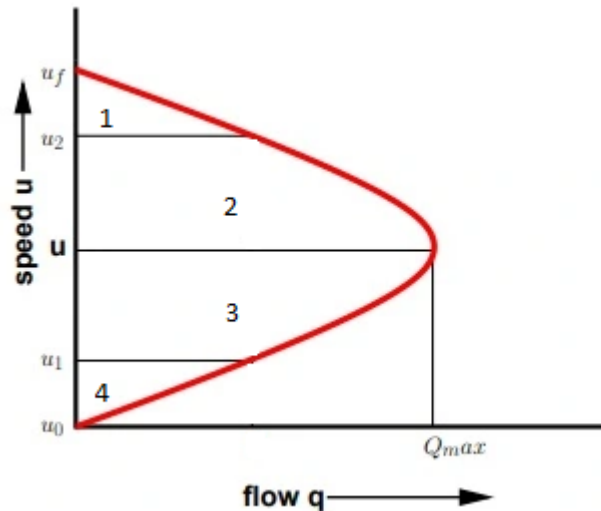
Figure 8: Fundamental Diagram Traffic Flow

The diagram can be divided into 4 distinct zones:

1. High speed and low flow zone: Speed is approaching free flow speed (uf) and flow is approaching zero. The traffic state in this zone is stable, the control system is off.

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2. Flow below capacity ($Qmax$) and speed above critical velocity: Speed and flow become inversely related as speed becomes the limiting factor. The traffic state in this zone is stable, the control system is off.

3. Speed below critical and flow below maximum: The traffic state is unstable, and bottlenecks can start to form that lead to congestion. The system is turned on to regulate the flow in order to return to a stable state.

4. Fully congested state: The speed and flow approach zero and the system is not effective anymore and is turned off.

To prevent congestion overflow onto the road network, an extra deactivation requirement was added, which means the system will turn off when neither activation requirement is satisfied or when the on-ramp is entirely congested with queued vehicles. When the system is initiated the ramp metering is turned on and the communication module starts transmitting instructions to CACC-equipped vehicles. The activation/deactivation of either system is linked with the other.

The concept of the control algorithm is that when high demand/congested conditions are detected the system begins metering the ramp vehicles and attempts to homogenize the gaps between vehicles on the motorway. This gap control is done by an instruction to CACC-equipped vehicles to leave a specific headway distance. The ramp metering is formulated to allow only a single vehicle at a time to enter the motorway during each green cycle if it can successfully accelerate and merge into a gap in the mainline flow. The gap is measured by a loop detector upstream of the merging section, sufficiently far to allow for the acceleration of either vehicle class.

To choose the location of the detector, three values need to be calculated:

1. The acceleration time of a ramp vehicle to merging speed. This is calculated assuming an initial speed of 0 km/h and a desired merging speed as a fraction of the mainline speed. The acceleration profiles used for each vehicle type are VISSIM standard. HGV acceleration rates are different from passenger vehicles, so vehicle identification at the RM installation is required, which can be done with number plate identification or using loop detectors to differentiate by length;

2. The distance the vehicle travels in that time. Calculated based on the value in 1;

3. The distance a vehicle on the mainline travels in that time. This is calculated assuming a fixed speed for the vehicles on the motorway.

The location of the gap measurement detector can then be found by the difference between 3 and 2. To avoid the installation of an additional detector for differential gap detection between vehicle classes, the calculation uses the most unfavourable values, which correspond to the HGVs. The gap detection for both classes is then done by a single detector, and the control algorithm distinguishes between the vehicle type and calculates the timings accordingly.

Another issue presents itself if a gap is found for HGVs closely followed by a gap for passenger vehicles. The faster-moving vehicle cannot overtake the slower one on the ramp, so a safety factor is implemented that specifies a minimum waiting time if the last vehicle released onto the ramp, is an HGV. This factor is calculated by the difference in the acceleration times of HGVs and passenger vehicles.

The complete logical control structure is presented in Figure 9.
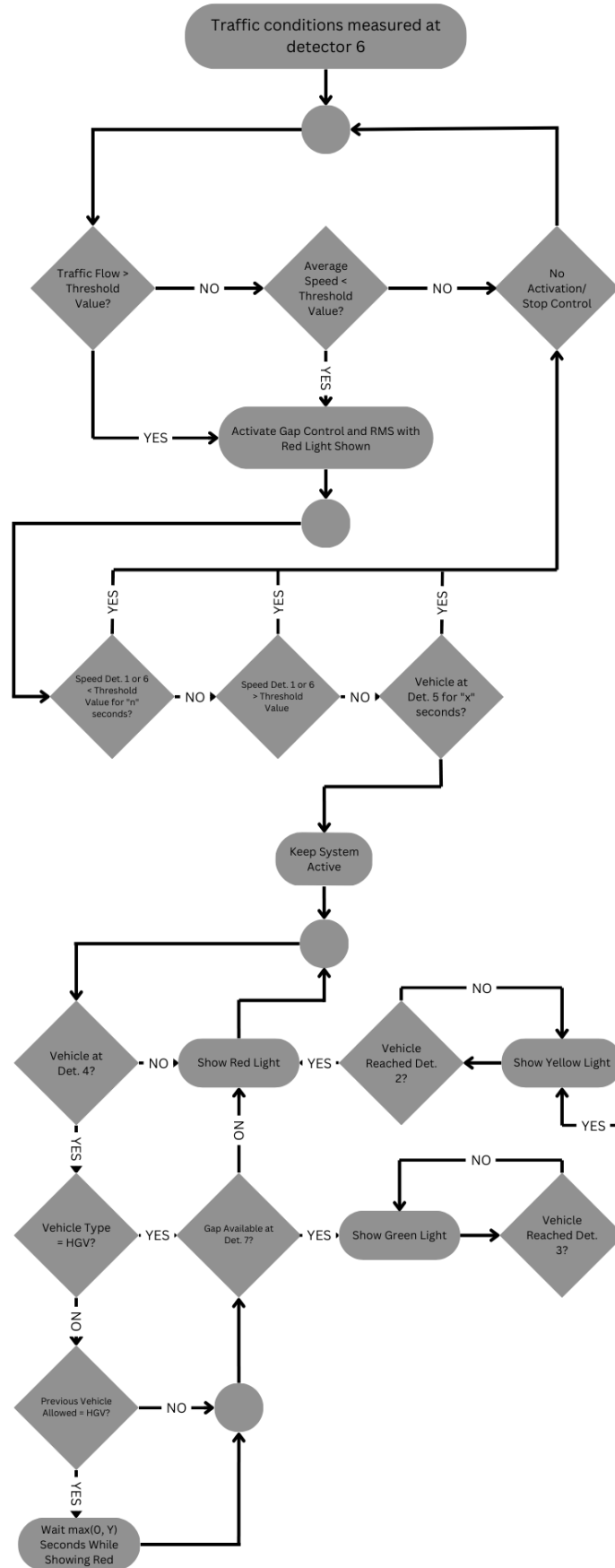
Figure 9: Control Algorithm, repeats every simulation cycle (Detectors referenced from Table 6 and Figure 7)

3.5. CACC HOMOGENIZATION

Module 2 of the control system, the computational module, handles the calculation of ramp metering rates based on gap detection and traffic state data supplied by the loop detectors. When the module detects a sufficient gap in the mainline flow it calculates the release timing of the ramp vehicle based on the vehicle types of both the ramp and motorway vehicles. Module 3, the communication module, handles the I2V communication to CACC equipped vehicles.

When the system is initialized, it begins transmitting instructions to supported vehicles to regulate the headway gap. This can be achieved with two different yielding strategies:

1. Keep One Vehicle Gap (KOV), instructs the vehicles to keep a vehicle gap in front even after the merging of the ramp vehicle;

2. Allow One Vehicle in Front (AOV), commands the vehicles to resume normal headway distance after the merger of a single vehicle in front.

The first strategy has problems, as drivers may be more unlikely to comply with this option and make the road users more frustrated which reduces support for the system. For the case study the second strategy will be used in the simulations.

3.6. SIMULATION

The algorithm described above is a microscopic RMS control strategy and, as such, needs to be simulated with resource to a microscopic simulation program.

For this study, VISSIM was chosen as the simulation program to model and simulate the microscopic RMS control strategy. VISSIM is an appropriate option for several reasons.

Firstly, it is a well-established simulation program that has been validated against real-world data. Secondly, VISSIM's user-friendly interface makes it accessible, even with limited time and resources. This allows efficient simulation of the complex traffic system involved in the RMS control strategy. Finally, VISSIM's advanced features, such as its ability to model complex traffic scenarios, make it suitable for simulating the RMS control strategy, which requires a high level of detail and accuracy.

3.7. ACCELERATION PROFILES

In VISSIM, acceleration profiles are described by mathematical functions that capture the change in velocity over time. These functions can be created using various mathematical models, such as polynomials or linear equations, and can be tailored to fit the specific requirements of the simulation.

Using acceleration profiles in VISSIM offers several advantages. Firstly, it enhances the accuracy of the simulation by simulating realistic acceleration and deceleration patterns that more closely resemble real-world driving behaviour. This can help identify potential traffic bottlenecks and congestion points, providing valuable insights for network optimization.

Secondly, acceleration profiles allow for studying the effects of different traffic management strategies. By adjusting the acceleration profiles of specific vehicle types or groups, it becomes possible to analyse the impact of different speed limits or traffic control measures on network performance. This can help identify the most effective strategies for reducing congestion, improving safety, or minimizing fuel consumption.

In the case study, VISSIM standard acceleration profiles will be used for the simulations, although proper calibration of these profiles is preferred in future research.

3.8. CALIBRATION

Calibrating a model in VISSIM involves adjusting the model parameters so that it accurately reflects real-world traffic conditions. The model needs to be as accurate to real life dynamics as feasable for the results to be valid and relevant. To calibrate the model, several steps need to be followed:

1. Collect data: Collect traffic data such as intensity, speed, and density from the real-world detectors on location;

2. Define the network: Set up the VISSIM model with the road network, including lane widths, on-ramps, and other elements;

3. Set up the demand: Define the demand in VISSIM by specifying the traffic volumes, origins, and destinations for each vehicle type;

4. Run a simulation: Run a simulation of the VISSIM model using the demand data and compare the output to the collected data;

5. Adjust parameters: Adjust the model parameters such as car-following behaviour, lane-changing behaviour, and acceleration values to better match the simulation output with the collected data;

6. Repeat: Run the simulation again with the adjusted parameters and compare the output to the collected data. Continue adjusting and running the simulation until the output matches the collected data.

3.9. SCENARIO PARAMETERS

To accurately evaluate the effectiveness of the control strategy some parameters need to be adjusted until the best possible performance is found. These parameters will help in understanding the viability and reliability of this approach. Three main variables will be employed:

1. Time headways will be used to regulate the gaps between vehicles on the merging section, to understand what the most effective headway distance for merging is. The time headway depends on the vehicle type, and so values need to be defined accounting for the desired speed and the standard deviation;

2. Average speed and flow thresholds are essential for defining when the system is active and are essential in optimizing the system operation. If incorrectly defined, the system can result in a network decrease in performance instead of an improvement;

3. The demand of the system is one of the most important variables to study, as the system can be beneficial in high demand situations and detrimental at lower demand values. It is then crucial to define the range where the model should be used.

The adjustment of these factors results in the optimal performance of the algorithm, which will then be compared with a control and base scenario to evaluate the possibility and benefits of such an approach.

3.10. MODEL EVALUATION PLAN

Model evaluation is a critical step in the performance evaluation plan for a VISSIM model. It involves comparing the model's simulated output to real-world traffic data and assessing the accuracy and effectiveness of the model. The objective of this step is to ensure that the model accurately represents the real-world traffic conditions and can be used to develop effective traffic management strategies.

Sensitivity analysis is another important component of model evaluation. By varying the model's input parameters and observing how they affect the model output, traffic engineers can identify the most critical parameters and ensure that they are accurately represented in the model. Scenario testing can also be used to evaluate the model's performance under different traffic conditions or management strategies.

Finally, model validation is an important part of model evaluation. Validation involves comparing the model's output to new data that was not used in the model development or calibration process. This can help ensure that the model is accurate and reliable over a wide range of traffic conditions.

In this dissertation, the model will also be evaluated against a control case (current situation/no RMS) and a comparison scenario (RMS without CACC).

3.11. KEY PERFORMANCE INDICATORS (KPIS)

In order to evaluate the performance of the developed control strategy, four key performance indicators were defined which are explained further in the next four points.

3.11.1. TOTAL TIME SPENT

Total Time Spent is one of the most common control indicators. It gives a numerical value to the total travel time of all vehicles on the network with the total waiting time at the ramp. This measure is often used to assess the level of service provided to vehicles on a particular route or network. In general, lower total time spent indicates better network performance, as it means vehicles can move through the network more quickly and with fewer delays. Measured in hours (h).

3.11.2. TOTAL DELAY

Delay refers to the amount of time that a vehicle spends waiting in a queue or stopped in traffic at a particular point in the transportation system. Delay is typically measured as the difference between the actual travel time of a vehicle and the expected travel time under ideal conditions, such as free-flowing traffic with no congestion or traffic signals. This difference is then summed over all vehicles traveling on a particular route or through a particular area to calculate the total delay and is expressed in hours (h).

3.11.3. AVERAGE SPEED

The average speed of vehicles in the study area is calculated by dividing the total distance travelled by the time taken to travel that distance. This indicator is useful to identify bottlenecks in the network, indicate the level of congestion, and help evaluate the changes made to the network. For this study, the average speed was divided into the average motorway speed and the average individual speeds of the ramp entry roads. Expressed in kilometers per hour (km/h).

3.11.4. TOTAL THROUGHPUT

This metric compares the number of vehicles that can pass through a given section of a motorway in a given time period, measured in vehicles per hour (veh/h).

While this indicator is related to the previous one, they capture different aspects of network performance. A network with high throughput may still have long delays and high total time spent if it is congested, while a network with low throughput may have low total time spent if it is not heavily utilized. As such, both measures are important in assessing and optimizing traffic management in a network.

3.12. CONCLUSION AND LIMITATIONS

This chapter presents an in-depth overview of the control system. To provide clarity, a brief summary is offered. Additionally, limitations present in this research are provided.

The control system comprises three modules that facilitate the collection and analysis of data, control calculations, and communication with road users. Initially, the data collection and treatment module receives detector data and assesses its relevance by comparing it with predetermined threshold values. Upon determining that the system should be activated, the second module takes over to compute the ramp metering rate and CACC integration for optimal performance. Finally, the third module manages traffic light operation and I2V communication with CACC-equipped vehicles on the mainline, implementing the instructions obtained from the second module.

The study presents several limitations that must be considered in the interpretation of the results.

Firstly, the vehicle acceleration profiles utilized in the analysis are based on VISSIM standard models that can fail to represent real-world conditions. Secondly, the homogenous acceleration patterns for all vehicles within the same class (car, HGV) do not account for the diversity of driving behaviours in reality. Furthermore, the calibration process of the model solely relies on a dataset from a single detector on the motorway, and thus, origin-destination data should be utilized for a more accurate calibration. Additionally, the simulation of the strategy solely covers a specific set of conditions and time frames, neglecting potential traffic disruptions such as accidents or roadworks that could significantly impact the system's performance. Moreover, the accuracy of the driver following model and lane changing behaviour is limited by the VISSIM standard models. Finally, the evaluation of the system is restricted to the utilization of microsimulation software and a single location.

4

CASE STUDY

This chapter presents the case study that has been conducted to evaluate the performance of the algorithm described in chapter three. Firstly, an introduction is given in section 4.1. After, the location and methodology are described in section 4.2 and 4.3 respectively, followed by the simulation setup in section 4.4. After that, in section 4.5 the simulated scenarios are explained, and the results of said simulations presented in section 4.6. To finalize, the performance analysis is described in section 4.7 and the discussion of the chapter in section 4.8.

4.1. INTRODUCTION

The previous chapter's algorithm was evaluated on a section of a Dutch motorway with recurring congestion issues to assess its control strategy. This case study was conducted as a part of an existing project by Iv-Infra B.V, commissioned by the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat). Several steps were undertaken to develop this case study.

The aim of the case study was to scrutinize the developed control strategy for the merging segment of an on-ramp situated in a congested stretch of motorway in The Netherlands. Rotterdam, being one of the prominent work and economic centres in the country, hosts the largest seaport in Europe (Port of Rotterdam) and a densely populated industrial and business area, making it one of the most heavily congested regions in the country. Consequently, predictions depict an increase in both passenger and freight traffic in the next few years, which worsens the already limited road capacity.

The chosen location for this study is on-ramp 24 (Rotterdam-Feijenoord), which connects the A16 with two heavily trafficked roads (Adriaan Volkerlaan and S106). This location satisfies all the required criteria, including an absence of ramp metering systems, a lengthy ramp for vehicle storage, and a downstream free-flowing section. Additionally, the presence of a parallel road with two lanes for local traffic separate from the two lanes for through traffic makes simulations simpler. Despite the parallel road, daily congestion is still prevalent, making it a suitable location for this study.

4.2. LOCATION OF THE CASE STUDY

As depicted in Figure 10, the congestion on the ring road encircling the city is heavily present during the evening peak, with similar results seen in the morning peak as well.
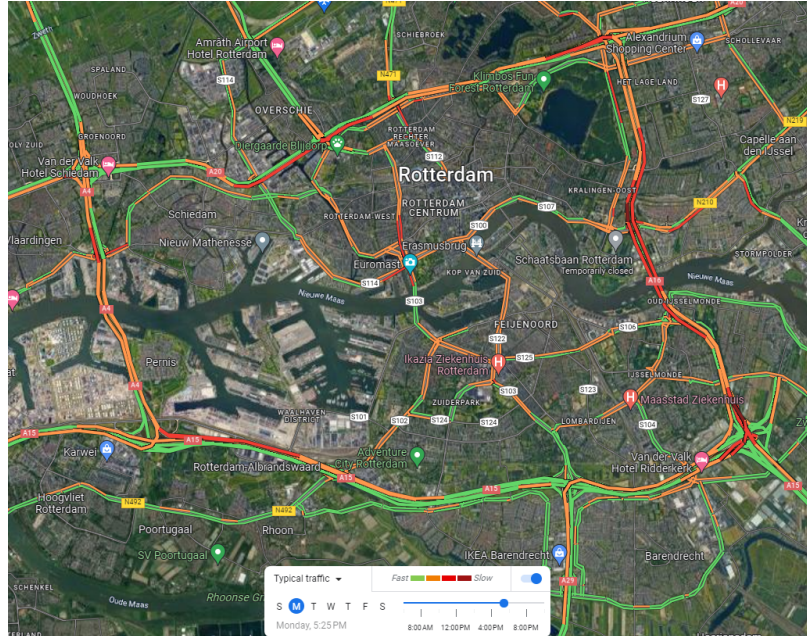
Figure 10: Congestion in Rotterdam (Source: Google Maps)

This makes the Rotterdam ring road a good candidate for the study of the effects of this control strategy. For this, a suitable on-ramp location was chosen based on five criteria:

1. Congestion: the location must be experiencing recurring congestion problems;

2. Simplicity: the focus of the case study is to study the viability of the strategy, so a simple network is desired;

3. No RMS: for the evaluation of the system comparison between the current and proposed scenarios is required, so a location with no ramp metering system is preferred;

4. Ramp Length: the strategy requires sufficient ramp length for acceleration and storage capacity;

5. No congestion downstream: the traffic state downstream of the chosen location must not also be regularly congested as it would negate the effects of the traffic management upstream.

Following these principles, a location on the A16 south was chosen (Figure 11).
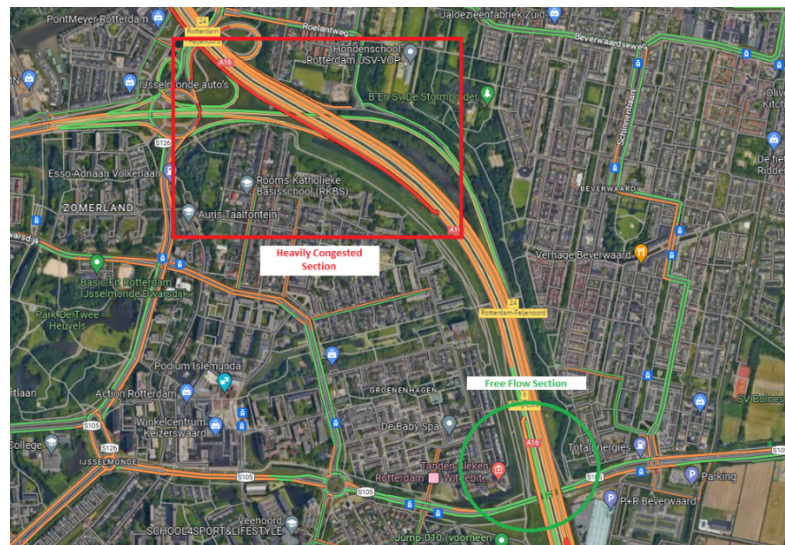
Figure 11: A16 Location (Source: Google Maps)

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4.3. METHODOLOGY

Initially, the location criteria were defined, and a site was chosen that lacked an existing RMS with a two-way parallel road motorway section that facilitated the simulation process. Subsequently, a network was created in VISSIM, with all infrastructure placed according to project needs and local regulations. To minimize simulation complexity and potential conflicts, some simplifications were made, which are further elaborated in section 4.4.

Next, the algorithm was coded in Python using the VISSIM Component Object Model (COM) interface. Control values such as flow and speed thresholds were required for the algorithm to run, and these values were determined based on a analysis done using OPTUNA, a Multi-Objective Optimization (MOO) framework for python. This variable optimization is critical to achieve maximum performance out of the strategy, where the calibration trades computation time with iteration number, as more iterations are better to achieve better adjusted parameters but take longer to do so. For this study 50 iterations were performed. The values are explained in further detail in section 4.4.4.

Once the variables were optimized, three scenarios were simulated to compare the control strategy with and without CACC and a no-control option. Each scenario was simulated ten times to account for stochastic variation, and the results averaged. The scenarios and their results are explained in detail in sections 4.5 and 4.6, respectively. The performance was then evaluated based on the previously defined KPIs in section 4.7.

In this study, a quantitative research approach was utilized to gather data from detectors that were already in place at the research location. The NDW Dexter database was the primary source of data for four loop detectors, with two located on the parallel road of the motorway and two on the on-ramp (Figure 12). Minute-data was chosen to ensure accuracy and consistency, and specifically a regular Thursday to avoid any anomalies that may arise from early week high traffic patterns or low demand end-of-week traffic. The data was compared with yearly averages to guarantee data relevance and accuracy.
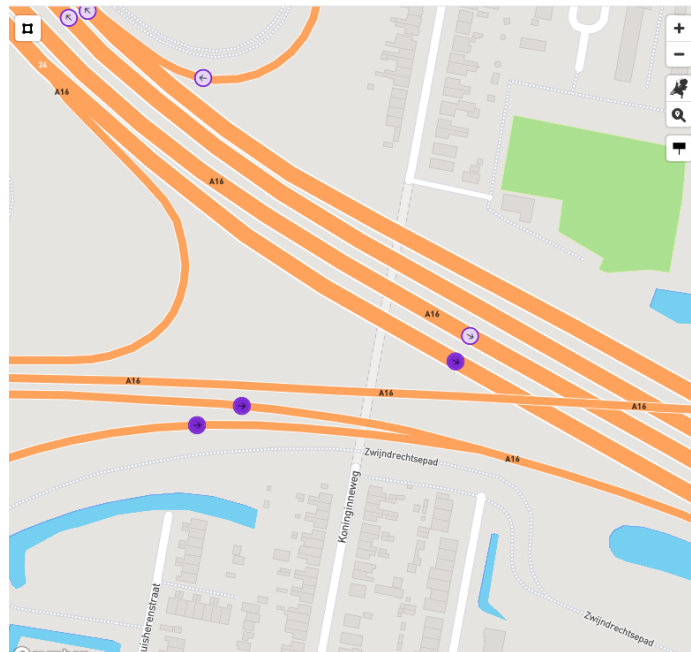
Figure 12: On-Site Detector Locations (Source: NDW Dexter)

The obtained minute-data was categorised by vehicle length, lane, observed vehicles (number of vehicles that passed through the detector within the time frame in veh/min), mean intensity (observed

vehicles extrapolated to veh/h) and mean speed (average speed of the vehicles that passed through the detector in that time frame).

A limitation of the data at the chosen location comes from the lack of downstream detectors across all lanes of the parallel road, which limits the analysis to the upstream detectors. As congestion happens downstream of the detectors, the measured traffic flow and capacity are not representative of the actual road conditions. As such, an artificial increase of 50% in traffic volumes was implemented to approximate the simulated congestion to the congestion observed in the data.

The data was then filtered for morning peak hours (07:00 a.m. – 09:30 a.m.) and afternoon peak hours (03:00 p.m. – 08:00 p.m.) based on typical traffic conditions observed through Google Maps.

4.4. SIMULATION SETUP

To conduct simulations, there were several important steps to follow. Firstly, the VISSIM network model was created, ensuring that the RMS and loop detectors were placed in the correct locations according to the design and project specifications. The control strategy is then linked by means of the VISSIM COM interface, programmed in this case, using the Python programming language. Next, the input parameters were specified based on parameter optimization. Finally, the scenarios were be simulated, and the results evaluated.

To ensure the generalizability of the proposed traffic control strategy, some simplifications were made to the network. Specifically, the location features two consecutive merging sections (Figure 13). However, to avoid introducing additional complexity, only the first merging section will be simulated. Furthermore, the through road will not be simulated, as local access is facilitated by the parallel road.
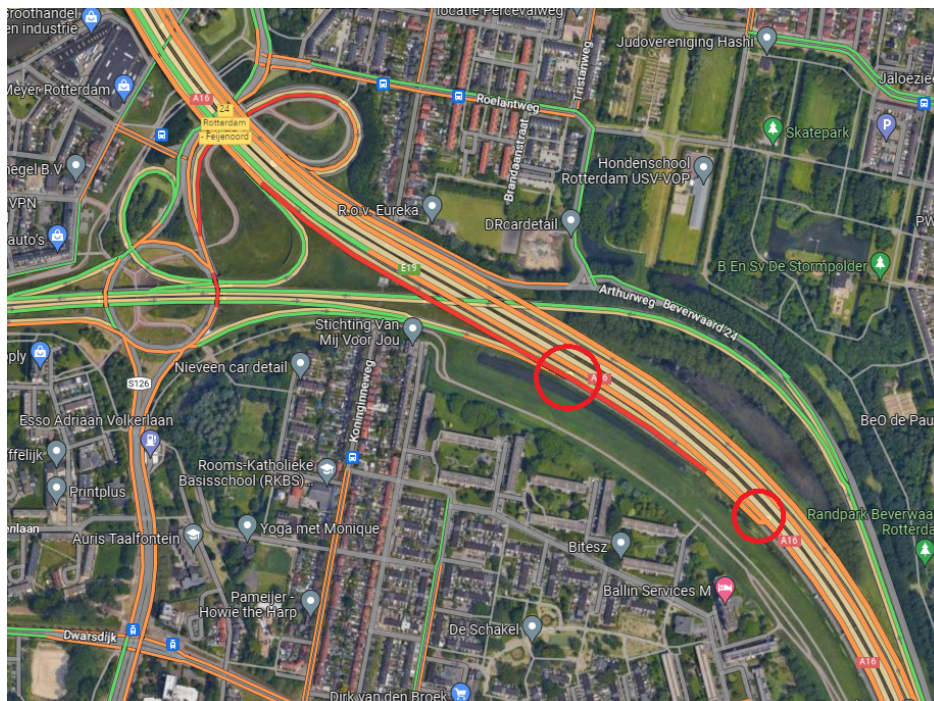
Figure 13: Merging Sections (Source: Google Maps)

The on-ramp was simplified in the network as well since the current setup would cause problems as the local guidelines and project calculations would require the stop line to be located at the merging section of the two lanes (Figure 14).

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Figure 14: Required RMS Location for Existing Network (Source: Google Maps)

Implementing the traffic control strategy at this location would present challenges in terms of timing, as there are two potential options for control. If both lanes receive a green signal simultaneously, timing issues may arise due to potential merge conflicts. On the other hand, independent green signals for each lane may lead to problems with priority assignment. To circumvent these issues, a simplification was implemented by moving the merging section upstream, allowing for the installation of a single-lane ramp metering system (Figure 15).

Figure 15: Simplified On-Ramp Merging Section

The RMS traffic light was therefore placed 250 meters upstream of the start of the merging section, assuming a -2% gradient estimated using Google Earth Pro, and according to the manual on preparation and implementation of ramp metering systems *(Handleiding voorbereiding en uitvoering toerit-doseerinstallaties)*.

4.4.1. NETWORK MODEL

The network was elaborated in VISSIM, only modelling the parallel road and on-ramp with the merger of the two roads upstream of the real-world network as mentioned in the section above (Figure 16).

Figure 16: Network Model

Another modification to the original network was the prohibition of lane changes from the left lane to the right lane of the parallel road of the motorway. The reverse does not happen, vehicles are free to go from the right to the left lane (Figure 17). This alteration is required to guarantee the gaps created/detected do not get occupied by the left lane vehicles, making the strategy ineffective. This exclusion starts at the upstream off-ramp and ends shortly after the end of the merging section. By outlawing these movements shockwaves can also be prevented from suboptimal merging.

Figure 17: Motorway Left Lane Movement Restriction

It should be noted that some assumptions and simplifications were necessary to reduce the complexity of the simulations. For instance, perfect driver behaviour was assumed, and other vehicle types such as motorcycles were not considered. Moreover, the simulations assumed a 100% compliance rate for traffic

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lights. The accuracy of the simulations was also limited by the use of Wiedemann's car-following models, which can fail to fully represent the complexities of driver behaviour.

4.4.2. INPUT DATA

The simulations relied on input parameters such as volume, vehicle composition, and relative flow. The traffic volumes were divided into three inputs, with one input for the motorway upstream and one each for the on-ramp origins. These volumes were determined by analysing detector data from NDW DEXTER and followed a stochastic distribution. Vehicle composition was limited to cars and Heavy Goods Vehicles (HGVs) with relative flows of 96.3% for cars and 3.7% for HGVs based on the analysed distribution in the data. The desired speed distribution for cars followed VISSIM standards for a 100 km/h speed limit, which ranged from 88 km/h to 130 km/h. The speed distribution for HGVs was considered to be 85 km/h, with a maximum of 88 km/h and a minimum of 84 km/h.

4.4.3. OUTPUT DATA

The output data was the total network throughput, average speed, and the total delay and time spent by vehicles on the motorway and on-ramp. From each scenario, the results were averaged across all simulations.

4.4.4. PARAMETER OPTIMIZATION

To get the best possible performance of the control algorithm 10 parameters were optimized using OPTUNA. 50 simulations were performed to balance accuracy and simulation time. Vehicle input volumes were set to exact, and the simulation seed was kept constant to assure a valid optimization. The best solution was picked based on maximization and minimization of the outputs (Table 7).

Table 7: Outputs

Outputs	*Total Travel Time*	*Total Delay*	*Avg. Speed Motorway*	*Avg. Speed Ramp 1*	*Avg.Speed Ramp 2*	*Total Throughput*
Objective	Minimize	Minimize	Maximize	Maximize	Maximize	Maximize

The parameters chosen for optimization were:

1. Avg. Speed Low Threshold: Lower limit for activation of control. Upper and lower values chosen based on analysis of the available data. Measured in seconds (s);

2. Avg. Speed High Threshold: Higher limit for activation of control. Upper and lower values chosen based on analysis of the available data. Measured in seconds (s);

3. Flow Threshold: Flow limit for activation of control. Upper and lower values chosen based on analysis of the available data. Measured in vehicles per hour (veh/h);

4. Activation time: Time between activation/deactivation tests. The bigger the activation time the longer it takes for the system to turn on/off after conditions are met, but the more stable and consistent is the system. Lower activation time increases fluctuations. Measured in seconds (s);

5. Margin: Margin of safety to account for the variation in the time vehicles take to get from detector 7 and RMS stop line to the beginning of the merging section. Measured in seconds (s);

6. RMS-to-Merge Car: Time it takes a car to arrive from RMS stop line to the beginning of the merging section. Upper and lower values chosen based on average values found using VISSIM's vehicle travel time measurements. Measured in seconds (s);

7. RMS-to-Merge HGV: Time it takes a HGV to arrive from RMS stop line to the beginning of the merging section. Upper and lower values chosen based on average values found using VISSIM's vehicle travel time measurements. Measured in seconds (s);

8. Det. 7-to-Merge Car: Time it takes a car to arrive from detector 7 to the beginning of the merging section. Upper and lower values chosen based on average values found using VISSIM's vehicle travel time measurements. Measured in seconds (s);

9. Det. 7-to-Merge HGV: Time it takes a HGV to arrive from detector 7 to the beginning of the merging section. Upper and lower values chosen based on average values found using VISSIM's vehicle travel time measurements. Measured in seconds (s);

10. Queue Time limit Det. 5: Time limit of detector 5 activation before system is turned off to flush ramp queue. Needs to balance queue length and waiting times with mainline capacity to achieve optimal performance. Measured in seconds (s).

The chosen parameters and their ranges are presented in Table 8:

Table 8: Parameter Range

Parameters	Lower Limit	Higher Limit
Avg. Speed Low Threshold (km/h)	20	40
Avg. Speed High Threshold (km/h)	70	90
Flow Threshold (veh/h)	2000	3500
Activation time (s)	120	300
Margin (s)	0	1
RMS-to-Merge Car (s)	15	16
RMS-to-Merge HGV (s)	18	19
Det. 7-to-Merge Car (s)	15	16
Det. 7-to-Merge HGV (s)	19	20
Queue Time limit Det. 5 (s)	120	300

The optimization results are presented in Table 9 and the corresponding parameters in Table 10.

Table 9: Optimization Results (Best Output)

Outputs	Total Travel Time (h)	Total Delay (h)	Avg. Speed Motorway (km/h)	Avg. Speed Ramp 1 (km/h)	Avg.Speed Ramp 2 (km/h)	Total Throughput (veh)
Solution	263.8	160.1	90	47	38	10445

Priority was given to the minimization of total travel time and delay, and average speed on the motorway is prioritised over the on-ramp access roads.

Table 10: Optimization Results (Parameters)

Parameters	Solution
Avg. Speed Low Threshold (km/h)	29.3
Avg. Speed High Threshold (km/h)	71.3
Flow Threshold (veh/h)	2999
Activation time (s)	222
Margin (s)	0.7
RMS-to-Merge Car (s)	15.3
RMS-to-Merge HGV (s)	18.2
Det. 7-to-Merge Car (s)	15.6
Det. 7-to-Merge HGV (s)	19.2
Queue Time limit Det. 5 (s)	176

4.5. SCENARIOS

In this section, an overview of the different scenarios conducted to evaluate the effectiveness of the control strategy is provided. The aim of these scenarios was to explore the impact of the proposed RMS algorithm with and without CACC in comparison to the existing situation:

1. Base/Control Scenario: This scenario represents the current situation with no RMS or control strategy in place. The input data comprised of traffic volumes, vehicle composition, and speed distribution;

2. RMS (no CACC): This scenario was simulated with the proposed control strategy. In addition to the input data of the base scenario, this scenario was implemented through the developed strategy using the parameters optimized in the previous section;

3. RMS (with CACC): This scenario was simulated with the proposed control strategy. It used the same input data as the Control Scenario and the same parameters as the RMS no CACC scenario. The difference is the usage of CoEXist parameters of the Wiedemann 99 model to simulate a CACC system in place.

For scenario 2 standard parameters were used for the car following model, with scenario 3 requiring a change in parameters CC0 to CC6 to simulate CACC behaviour (Table 11). These parameter settings were chosen based on the CoEXist project by the EU (Sukkenik et al., 2018), to define default behavioural parameter sets for AVs. These parameter sets are implemented as standard in VISSIM.

Table 11: Wiedemann 99 Parameter Settings

Parameters	Scenario 2	Scenario 3
CC0	1.5 m	1.5 m
CC1	0.9 s	0.9 s
CC2	4 m	0 m
CC3	- 8 s	- 8 s
CC4	$- 0.35 \frac{m}{s}$	$- 0.1 \frac{m}{s}$
CC5	$0.35 \frac{1}{m*s}$	$0.1 \frac{1}{m*s}$
CC6	$11.44 \frac{m}{s^2}$	$0 \frac{m}{s^2}$
CC7	$0.25 \frac{m}{s^2}$	$0.1 \frac{m}{s^2}$
CC8	$3.5 \frac{m}{s^2}$	$3.5 \frac{m}{s^2}$
CC9	$1.5 \frac{m}{s^2}$	$1.5 \frac{m}{s^2}$

In the Wiedemann 99 model a vehicle aims at keeping a safety distance given by $d_{safe} = \text{CC0} + \text{CC1} \cdot v$ where CC0 is the standstill distance and CC1 is the time gap between leader and follower that the follower tries to maintain.

The simulations were run for 2.5 hours, with a simulation resolution of 10 steps per simulation second. A total of 10 runs were performed to strike a balance between sample size and time requirements and to account for stochastic variation of the input data.

4.6. RESULTS

This section presents the findings and outcomes obtained from three different scenarios: the base scenario, the RMS without CACC scenario, and the RMS with CACC scenario. Each scenario was carefully designed and simulated to evaluate the impact of CACC and RMS on various performance metrics. This section aims to provide a comprehensive analysis of the results obtained, highlighting the differences observed among the scenarios and drawing meaningful conclusions regarding the effectiveness of CACC and RMS in improving traffic conditions.

In the next sections the simulation results of the three scenarios, Base/Control scenario, RMS without CACC and RMS with CACC, will be discussed in both the morning and afternoon peak.

4.6.1. BASE SCENARIO

In this section, the results of the simulation study will be presented, focusing specifically on the control scenario. The control scenario plays a crucial role as it serves as a baseline for comparing the performance of alternative strategies or interventions. By establishing the control scenario, the effectiveness and impact of our proposed approaches is evaluated in relation to the existing method.

By analysing and presenting the results of the control scenario, a benchmark can be established against which we evaluate the efficacy and superiority of the proposed approaches. The control scenario acts as

a crucial point of reference, enabling us to draw meaningful conclusions and make informed recommendations based on the observed differences and improvements.

In the subsequent sections, the morning and afternoon peak results obtained from the control scenario will be analysed in detail, including a discussion of the implications and limitations of the results. This analysis will shed light on the strengths and weaknesses of the control scenario and make for a thorough comparison with the alternative scenarios or interventions that we explore in the subsequent sections.

4.6.1.1. MORNING PEAK

The simulations were run 10 times with different seeds to account for variability in vehicle input volumes. As mentioned in section 4.3, an artificial increase of 50% in all vehicle input volumes (motorway + access roads) were implemented to account for the limited data available (

Table 12). This increase was applied to artificially increase the demand as the original data did not result in any congestion as expected in the observations (Table 13).

Table 12: Total Vehicle Input Volume (veh/h) - Morning Peak

5 min Interval	Original Data	150%
7:00:00	2244	3366
7:05:00	2892	4338
7:10:00	2928	4392
7:15:00	2784	4176
7:20:00	3228	4842
7:25:00	2772	4158
7:30:00	3084	4626
7:35:00	3240	4860
7:40:00	2568	3852
7:45:00	3192	4788
7:50:00	2796	4194
7:55:00	3324	4986
8:00:00	2844	4266
8:05:00	3252	4878
8:10:00	3264	4896
8:15:00	3240	4860
8:20:00	3120	4680
8:25:00	2856	4284
8:30:00	3552	5328
8:35:00	3144	4716
8:40:00	2952	4428
8:45:00	3072	4608
8:50:00	2436	3654
8:55:00	2364	3546
9:00:00	2100	3150
9:05:00	2016	3024
9:10:00	1764	2646
9:15:00	2388	3582
9:20:00	2040	3060
9:25:00	2268	3402

Table 13: Base Data Simulation Results (km/h) - Morning Peak

5 min Interval	Avg. Intensity Data	Avg. Speed Data	Avg. Speed Simulation
7:00:00	1620	106,88	105,161873
7:05:00	2184	103,565	103,503195
7:10:00	2280	102,195	103,310877
7:15:00	1956	103,31	103,751579
7:20:00	2592	102,905	103,469456
7:25:00	2148	100,115	104,012648
7:30:00	2364	95,155	103,992943
7:35:00	2436	53,93	103,623038
7:40:00	1944	43,205	103,268415
7:45:00	2424	17,17	104,463658
7:50:00	2076	18,505	104,83918
7:55:00	2724	50,925	103,23853
8:00:00	2280	103,43	103,868749
8:05:00	2496	102,335	103,649229
8:10:00	2508	102,175	104,352481
8:15:00	2604	105,09	103,496374
8:20:00	2460	101,725	102,766094
8:25:00	2148	104,56	104,36444
8:30:00	2676	102,87	104,6829
8:35:00	2544	103,655	103,454426
8:40:00	2280	104,145	104,688619
8:45:00	2340	102,26	104,981786
8:50:00	1764	105,935	104,744161
8:55:00	1908	105,14	104,659976
9:00:00	1608	105,015	103,785822
9:05:00	1536	106,395	106,011441
9:10:00	1404	106,65	106,019152
9:15:00	1884	106,025	104,780778
9:20:00	1584	104,21	105,548751
9:25:00	1704	105,97	104,396705

The simulation results of the control scenario can be found in Table 14.

Table 14: Control Simulation Results (Morning Peak)

Morning Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallelbaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	275,5	171,1	78,5	53,4	45,9	10445,0
2	272,8	168,2	80,0	52,3	43,3	10472,0
3	259,1	156,0	79,8	57,7	48,0	10334,0
4	318,8	212,5	73,3	46,9	41,2	10597,0
5	217,9	115,8	82,9	70,8	51,6	10254,0
6	293,2	187,2	74,0	55,4	49,2	10589,0
7	314,5	210,5	70,2	46,8	42,6	10360,0
8	267,5	163,5	96,2	38,9	39,2	10522,0
9	259,4	154,2	75,9	61,8	50,8	10515,0
10	298,5	193,4	72,3	54,9	48,3	10502,0
Avg.	277,7	173,2	78,3	53,9	46,0	10459,0
Range	100,9	96,8	26,0	31,9	12,4	343,0
Standard Deviation	30,0	29,1	7,4	8,8	4,3	111,9
Min.	217,9	115,8	70,2	38,9	39,2	10254,0
Max.	318,8	212,5	96,2	70,8	51,6	10597,0

A high variability can be observed in all performance indicators. A high range (difference between the maximum and minimum) of simulation results indicates that there is significant variation or uncertainty in the outcomes of the simulation. It means that when running the simulation multiple times with different inputs or parameters, the results obtained can differ widely from one another.

This variability is explained by various factors, such as the inherent complexity of the system being simulated, the inclusion of the stochastic variation within the vehicle input data, the sensitivity of the model to small changes in initial conditions or input parameters. A small variation in traffic volumes leads to dramatic increases in total travel time, by expediting the onset of congestion or by reducing the capabilities of the system to recover from that same congestion.

A high range of simulation results indicates that the outcomes are not consistently predictable or deterministic. Instead, the results span a wide spectrum, indicating that the system being simulated is influenced by multiple variables and exhibits complex behaviour.

4.6.1.2. AFTERNOON PEAK

Based on

Table 15, it is evident that the data indicates a notable increase in volume during the chosen time interval, reflecting severely degraded traffic conditions with high congestion levels.

These conditions pose challenges for improving performance as the traffic state is outside the system's efficiency range. Consequently, the performance indicators experience a decline during the afternoon peak, characterized by increased travel time and delay, and a decrease in average speed. Interestingly, vehicle throughput still improves despite the congestion, owing to higher input volumes (as shown in Table 16). Comparing delay and travel time per vehicle becomes crucial for assessing relative performance between scenarios, and this aspect will be further discussed in the performance analysis in section 4.7.

Table 15: Total Vehicle Input Volume (veh/h) - Afternoon Peak

5 min Interval	Original Data	150%
16:00:00	3180	4770
16:05:00	2940	4410
16:10:00	3348	5022
16:15:00	3288	4932
16:20:00	4164	6246
16:25:00	4092	6138
16:30:00	4188	6282
16:35:00	3552	5328
16:40:00	4248	6372
16:45:00	4068	6102
16:50:00	3612	5418
16:55:00	3576	5364
17:00:00	3168	4752
17:05:00	3252	4878
17:10:00	2832	4248
17:15:00	2796	4194
17:20:00	2928	4392
17:25:00	3384	5076
17:30:00	3180	4770
17:35:00	3672	5508
17:40:00	3276	4914
17:45:00	2808	4212
17:50:00	3396	5094
17:55:00	2808	4212
18:00:00	2136	3204
18:05:00	2604	3906
18:10:00	2772	4158
18:15:00	3576	5364
18:20:00	3684	5526
18:25:00	3348	5022

Table 16: Control Simulation Results (Afternoon Peak)

Afternoon Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallelbaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	459,8	346,8	52,6	22,5	24,0	11095,0
2	459,7	347,2	52,0	24,0	29,9	11069,0
3	462,9	349,5	54,2	18,4	23,6	11162,0
4	452,7	339,3	49,9	20,1	36,9	11142,0
5	456,6	344,1	50,7	21,6	35,2	11045,0
6	464,2	350,5	52,7	19,3	29,3	11208,0
7	449,2	335,8	47,5	24,0	33,7	11134,0
8	452,0	338,6	51,8	23,2	32,1	11155,0
9	452,0	339,2	51,3	21,7	35,3	11086,0
10	455,1	341,6	51,8	22,6	30,0	11165,0
Avg.	456,4	343,3	51,5	21,7	31,0	11126,1
Range	15,1	14,7	6,7	5,6	13,3	163,0
Standard Deviation	5,1	5,1	1,8	1,9	4,6	50,6
Min.	449,2	335,8	47,5	18,4	23,6	11045,0
Max.	464,2	350,5	54,2	24,0	36,9	11208,0

4.6.2. RMS (NO CACC)

This section focuses on presenting the simulation results from the second scenario. The second scenario utilizes the developed control strategy with the standard Wiedemann 99 parameters, without incorporating the CACC contribution. These simulations serve as an essential benchmark for assessing the impact of the system and comparing it with the performance of CACC.

By comparing the effects of the system with and without CACC, the impact of this technology can be quantified, and its potential benefits evaluated. This comparison allows us to determine whether the inclusion of CACC enhances the system's performance or if the standard strategy is preferred.

4.6.2.1. MORNING PEAK

The results in this scenario exhibit a similar trend as the base scenario, displaying a notable degree of variation and deviation, albeit slightly less pronounced. This observation is evident when examining the range and standard deviation values depicted in Table 17.

Table 17: RMS without CACC Simulation Results (Morning Peak)

Morning Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallebaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	263,8	160,1	89,6	46,7	38,4	10445
2	299,9	195,4	79,9	38,9	40,6	10472
3	249,3	146,1	75,7	62,8	47,9	10334
4	318,8	212,5	73,3	46,9	41,2	10597
5	245,2	143,1	83,4	61,7	48,8	10254
6	305,1	199,4	77,1	44,4	47,3	10589
7	314,5	210,5	70,2	46,8	42,6	10360
8	324,8	219,6	74,0	36,8	41,4	10522
9	281,2	176,6	84,6	43,8	42,9	10515
10	315,0	210,4	82,3	36,3	36,2	10502
Avg.	291,8	187,4	79,0	46,5	42,7	10459
Range	79,6	76,5	19,3	26,5	12,6	343,0
Standard Deviation	29,8	28,8	6,0	9,2	4,1	111,9
Min.	245,2	143,1	70,2	36,3	36,2	10254,0
Max.	324,8	219,6	89,6	62,8	48,8	10597,0

4.6.2.2. AFTERNOON PEAK

The results during the afternoon peak reveal an intriguing observation: the averages in this scenario are identical to those in the base scenario (Table 18). This suggests a significant failure of the system under these specific conditions. The degraded state of the network renders the control system incapable of generating any positive impact. Therefore, it is crucial to anticipate implementing the strategy during

periods of minimal congestion. Similar trends as the base scenario persist in this scenario, accompanied by the same limitations.

Table 18: RMS without CACC Simulation Results (Afternoon Peak)

Afternoon Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallelbaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	459,7	347,2	52,6	22,5	24,0	11095
2	459,7	347,2	52,0	24,0	29,9	11069
3	462,9	349,5	54,2	18,4	23,6	11162
4	452,7	339,3	49,9	20,1	36,9	11142
5	456,6	344,1	50,7	21,6	35,2	11045
6	464,2	350,5	52,7	19,3	29,3	11208
7	449,2	335,8	47,5	24,0	33,7	11134
8	452,0	338,6	51,8	23,2	32,1	11155
9	452,0	339,2	51,3	21,7	35,3	11086
10	455,1	341,6	51,8	22,6	30,0	11165
Avg.	456,4	343,3	51,5	21,7	31,0	11126
Range	15,1	14,7	6,7	5,6	13,3	163,0
Standard Deviation	5,1	5,1	1,8	1,9	4,6	50,6
Min.	449,2	335,8	47,5	18,4	23,6	11045,0
Max.	464,2	350,5	54,2	24,0	36,9	11208,0

It is important to acknowledge that, in terms of travel time, both the minimum and maximum values exceed those observed in the base scenario. Given that the throughput remains unchanged, it can be inferred that this scenario yields a decrease in overall performance. This outcome is unexpected, considering that the system aims to enhance traffic conditions through gap detection and ramp metering, even in the absence of the CACC component.

However, it is crucial to recognize several limitations inherent in the study that may contribute to these results. These limitations include a relatively low number of parameter optimization iterations, an insufficient simulation sample size, and the absence of Wiedemann parameter optimization. Considering these factors is essential when interpreting the observed outcomes.

4.6.3. RMS (WITH CACC)

In this section, we delve into the results obtained from the simulations incorporating CACC. To achieve this, the Wiedemann 99 parameter values were modified according to the coEXist standard. The primary objective of this dissertation is to evaluate the performance of this scenario, and as such, these results will be compared against those of the first and second scenarios discussed in Section 4.7.

4.6.3.1. MORNING PEAK

In contrast to the observations in the second scenario, the simulation results demonstrate a significant and noteworthy improvement when compared to both the base scenario and the standalone RMS control (Table 19).

Table 19: RMS with CACC Simulation Results (Morning Peak)

Morning Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallelbaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	216,0	113,1	99,1	49,1	41,5	10445
2	232,7	129,5	101,9	41,5	42,7	10472
3	184,4	82,5	99,9	62,4	50,7	10333
4	198,6	94,2	101,7	55,7	44,3	10597
5	203,0	102,2	102,3	52,9	46,6	10254
6	217,9	113,8	100,0	52,8	45,8	10590
7	201,9	99,8	101,5	55,5	44,1	10360
8	242,4	138,8	97,1	48,6	45,0	10522
9	200,1	96,7	98,1	59,2	45,7	10515
10	193,7	90,4	102,0	58,2	46,0	10502
Avg.	209,1	106,1	100,4	53,6	45,2	10459
Range	58,0	56,4	5,2	21,0	9,1	343,0
Standard Deviation	18,0	17,7	1,8	6,1	2,5	112,2
Min.	184,4	82,5	97,1	41,5	41,5	10254,0
Max.	242,4	138,8	102,3	62,4	50,7	10597,0

4.6.3.2. AFTERNOON PEAK

The afternoon peak results exhibit greater variability compared to the preceding afternoon scenarios, with significantly lower minimum and maximum values for the total travel time and delay (Table 20).

Table 20: RMS with CACC Simulation Results (Afternoon Peak)

Afternoon Peak	Total Travel Time (h)	Total Delay (h)	Avg. Speed Parallelbaan (km/h)	Avg. Speed Stadionweg (km/h)	Avg.Speed Volkerlaan (km/h)	Veh. Arrived (veh)
1	425,3	311,6	79,2	19,6	17,3	11405
2	416,8	301,6	76,6	23,4	22,6	11511
3	435,6	321,6	71,3	19,2	24,3	11353
4	425,5	310,3	75,5	18,2	21,9	11538
5	439,9	326,7	67,3	18,8	30,4	11258
6	434,8	320,6	76,9	18,8	19,4	11459
7	431,3	316,0	72,7	21,7	18,5	11483
8	458,0	343,8	67,7	20,3	18,1	11402
9	409,6	294,4	79,5	22,2	25,3	11540
10	400,8	285,4	79,7	23,4	22,2	11586
Avg.	427,8	313,2	74,7	20,6	22,0	11454
Range	57,2	58,4	12,4	5,2	13,1	328,0
Standard Deviation	16,2	16,7	4,7	2,0	4,0	99,8
Min.	400,8	285,4	67,3	18,2	17,3	11258,0
Max.	458,0	343,8	79,7	23,4	30,4	11586,0

4.7. PERFORMANCE ANALYSIS

This section aims to provide a comprehensive evaluation of the performance of the proposed system. In this section, the results presented previously will be compared and conclusions made. Furthermore, any limitations will be addressed and the potential implications of said limitations explained. By identifying and discussing these limitations a grounded and critical evaluation can be made.

4.7.1. SCENARIO COMPARISON

This section aims to provide context for the performance analysis by comparing the different scenarios during the morning and afternoon peak.

Examining Figure 18 and Figure 19, more consistent results can be observed during the afternoon peak. This can be attributed to the less significant impact of changes in traffic volumes when congestion is already high. Under these circumstances, an increase in demand does not exert as much influence on the traffic state as observed during the morning peak.
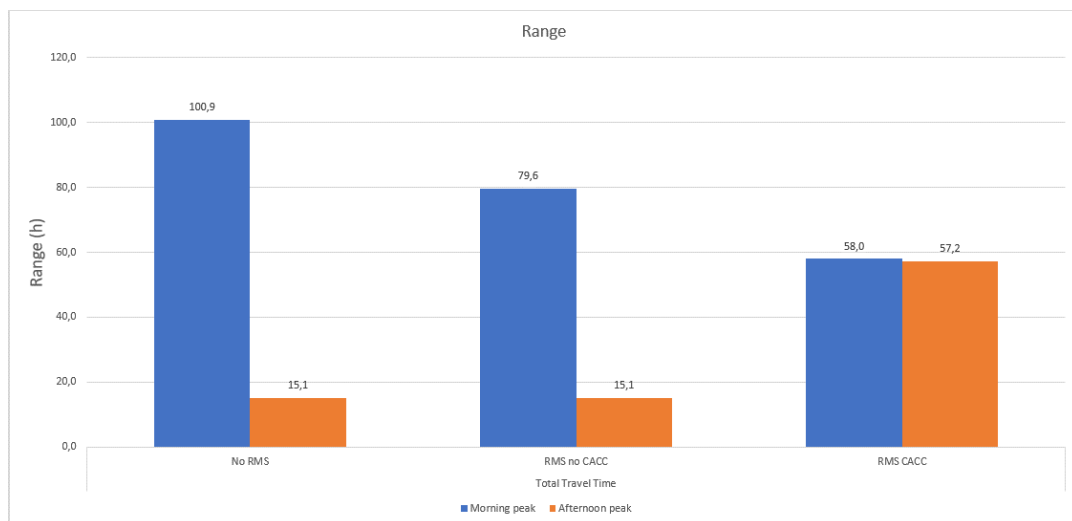

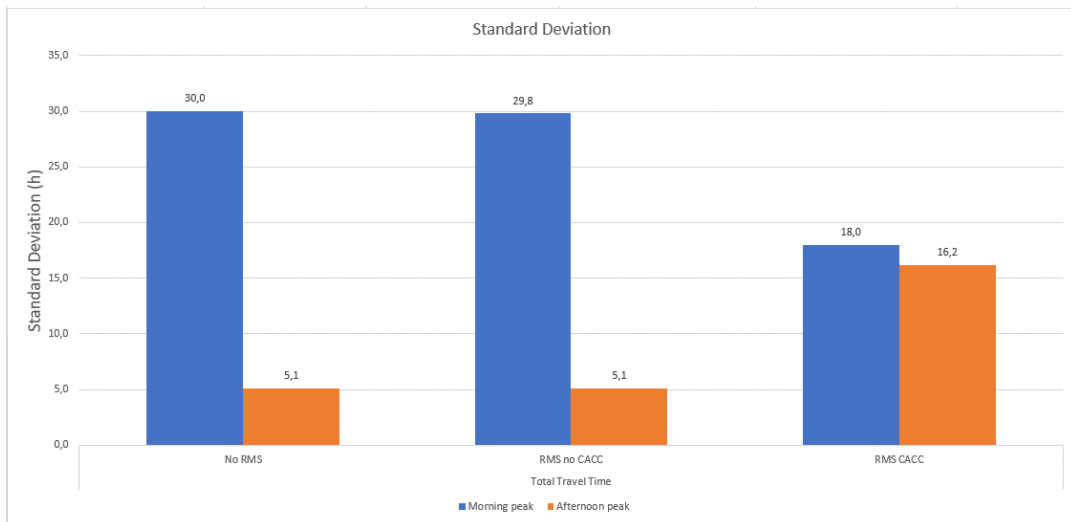Figure 18: Total Travel Time Range Distribution

Figure 19: Total Travel Time Standard Deviation Distribution

More uniform results can be observed from the RMS CACC scenario, as the simulation benefits from the CACC homogenization, which introduces less variation due to driver behaviour.

It is important though to acknowledge that this inconsistency presents a limitation in this study, as it introduces uncertainty when drawing conclusions about the system's performance.

4.7.1.1. MORNING PEAK

A notable thing to point out is that while the average speed of the motorway was slightly increased, the averages of the on-ramp access roads were slightly lowered (Figure 20). This can be attributed to the impact of ramp metering, as the system prioritizes maintaining smooth traffic flow on the mainline, potentially at the expense of reduced throughput on the on-ramps.
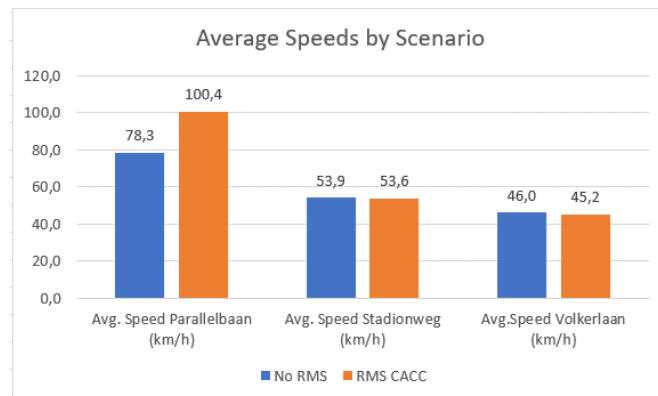
Figure 20: Avg. Speed Results in km/h (Scenario 1 and 2) – Morning Peak

The implementation of the system resulted in significant reductions in total travel time and total delay, accompanied by a substantial increase in the average speed of the motorway, as depicted in Figure 21. These findings demonstrate the successful functioning of the system according to its intended objectives.
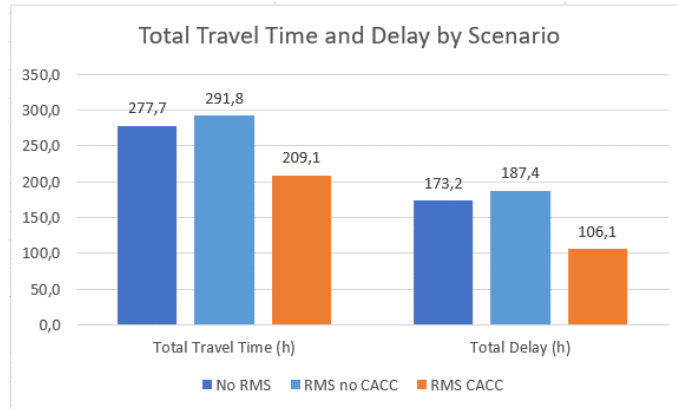
45

Figure 21: Total Travel Time and Delay Results in hours (Scenario 1, 2 and 3) - Morning Peak

The average speeds of the access roads to the on-ramp showed a slight decrease compared to the base scenario but demonstrated an improvement compared to the standard RMS system (Figure 22). However, it is important to note that this effect is negligible when considering the overall performance gain.
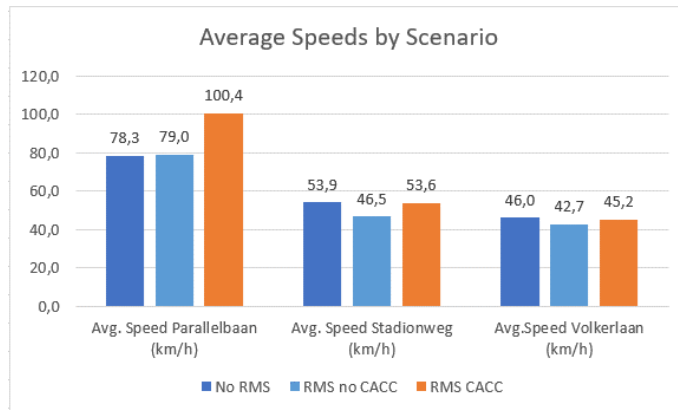

Figure 22: Avg. Speed Results in km/h (Scenario 1, 2 and 3) – Morning Peak

4.7.1.2. AFTERNOON PEAK

The effectiveness of the system in improving network performance becomes evident when analysing the afternoon peak results of average total travel time and delay, as shown in Figure 23. These findings strongly indicate that the system provides a significant net benefit to the overall performance of the network.
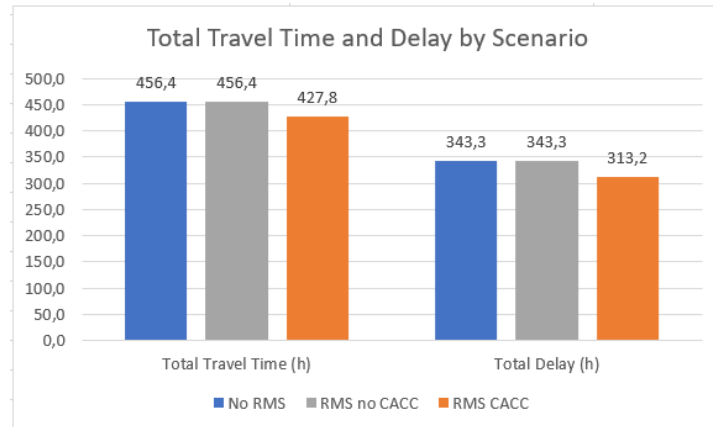
Figure 23: Total Travel Time and Delay Results in hours (Scenario 1, 2 and 3) - Afternoon Peak

The simulation results demonstrate a positive impact on the average speed of the motorway, as observed in Figure 24. Although there is a minimal decrease in average speed on the Stadionweg, a more substantial decrease is observed at the Volkerlaan entry point. This effect can be attributed to the merging of the Volkerlaan access road with the on-ramp, which often leads to queuing under congested conditions. The driving behaviours of users entering from the Stadionweg can contribute to this queue.
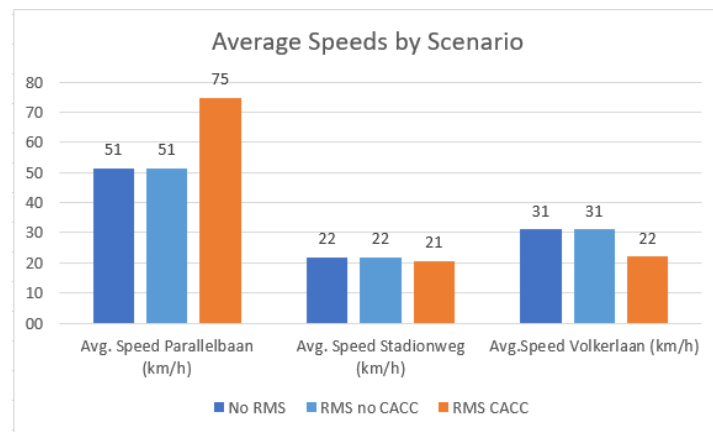

Figure 24: Avg. Speed Results in km/h (Scenario 1, 2 and 3) – Afternoon Peak

In contrast to the morning peak results, the afternoon findings reveal a notable enhancement in network throughput compared to both the control and no CACC scenarios. This improvement can be attributed to a reduction in congestion along the mainline, leading to smoother traffic flow and ultimately higher throughput (Figure 25).
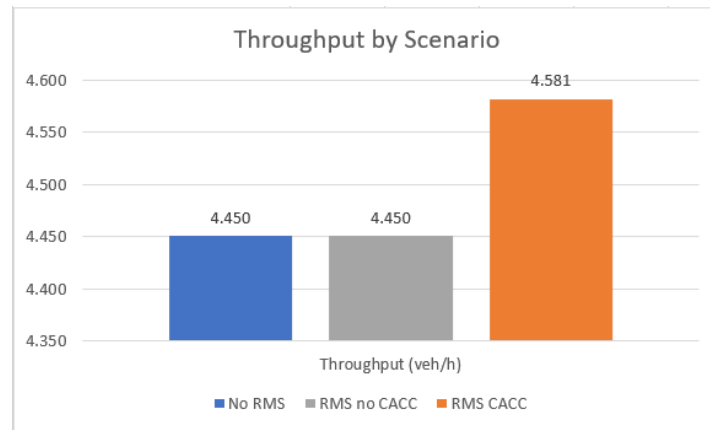
47

Figure 25: Throughput Results in veh/h (Scenario 1, 2 and 3) – Afternoon Peak

4.7.2. KEY PERFORMANCE INDICATORS

This section provides a comparison across the key performance indicators chosen for the system performance evaluation.

4.7.2.1. TOTAL THROUGHPUT

Comparing the total network output is a crucial aspect of the performance analysis. Figure 26 illustrates that the total throughput remains consistent across all scenarios during the morning and afternoon peaks, except for the RMS with CACC afternoon scenario, which exhibits an increase of approximately 1% in throughput. This observed improvement is negligible, which allows for this indicator to be used as a control variable to assure the results are comparable.
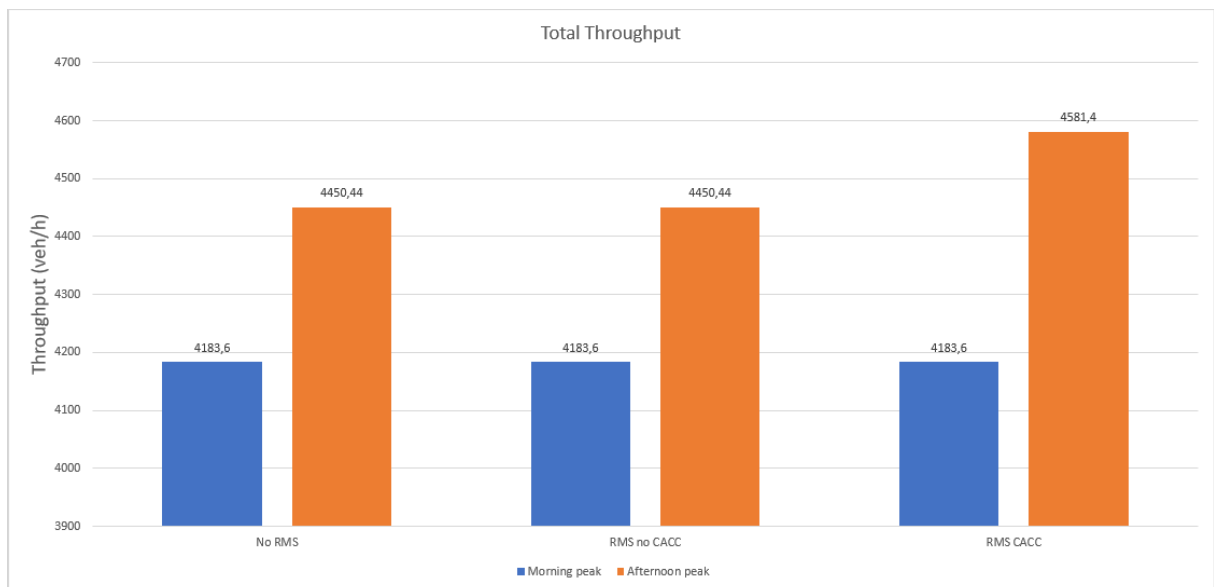

Figure 26: Total Throughput (veh/h)

4.7.2.2. TOTAL TRAVEL TIME

The results section reveals a significant reduction in total travel time when CACC is implemented when compared with the control scenario. Conversely, the result without the CACC component shows a

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notable increase in total travel time, as illustrated in Figure 27. This figure provides a comparative analysis of total travel time results across all scenarios.
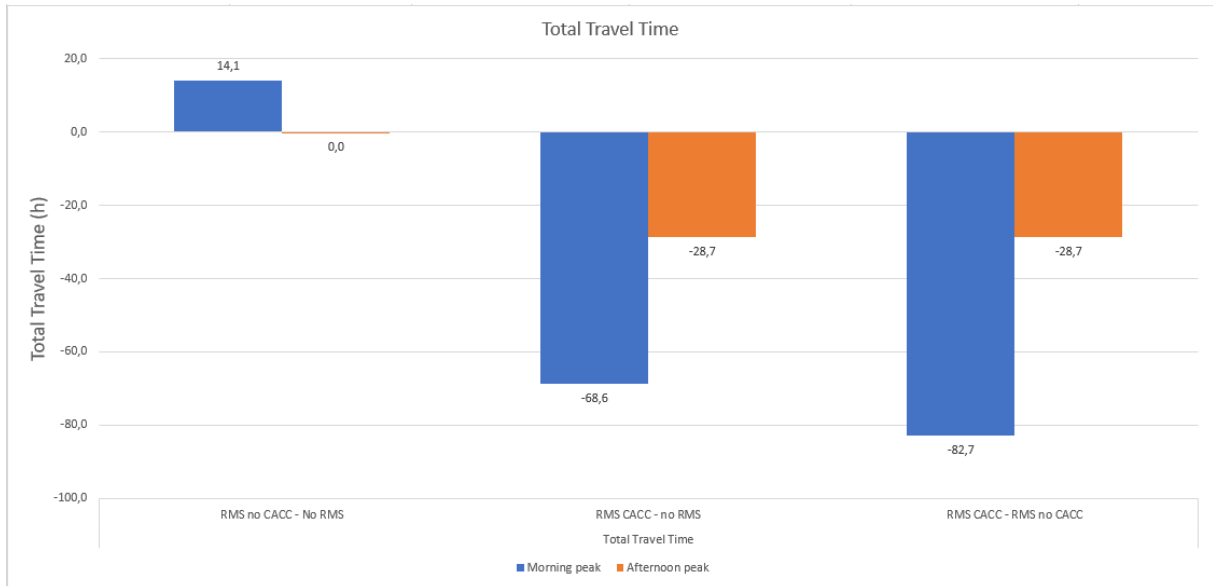

Figure 27: Total Travel Time Savings (h) - Morning and Afternoon

These findings are further illustrated through the visualization of average travel time savings per vehicle, as depicted in Figure 28.
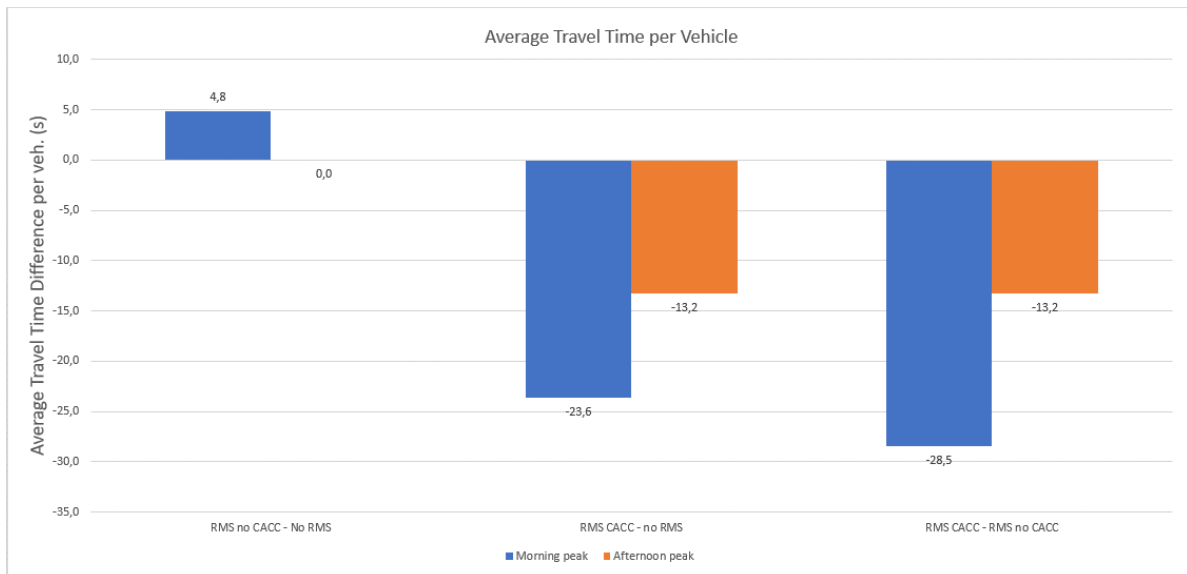

Figure 28: Average Travel Time Savings per Vehicle (s)

These average savings per vehicle can be translated into a percentual difference, as presented in Table 21.

Table 21: Total Travel Time Change (%)

Change	*Morning*	*Afternoon*
2 – 1	+ 5 %	0%
3 – 1	- 25%	- 9%
3 – 2	- 28%	- 9%

Another significant observation derived from this data is that the time savings during the morning peak are more than double compared to the afternoon peak. This discrepancy can be attributed to the congested nature of the afternoon peak, which restricts the effectiveness of the strategy and hinders the potential benefits.

4.7.2.3. TOTAL DELAY

The total delay exhibits a consistent pattern and values, mirroring the trends observed in the travel time savings, as depicted in Figure 29 and Figure 30.
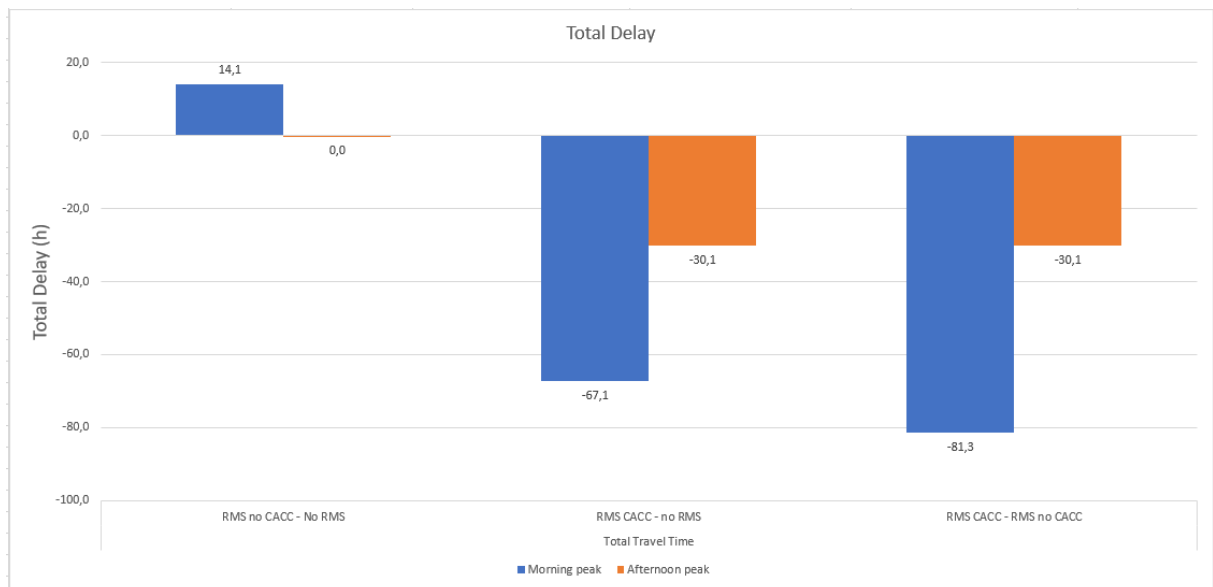

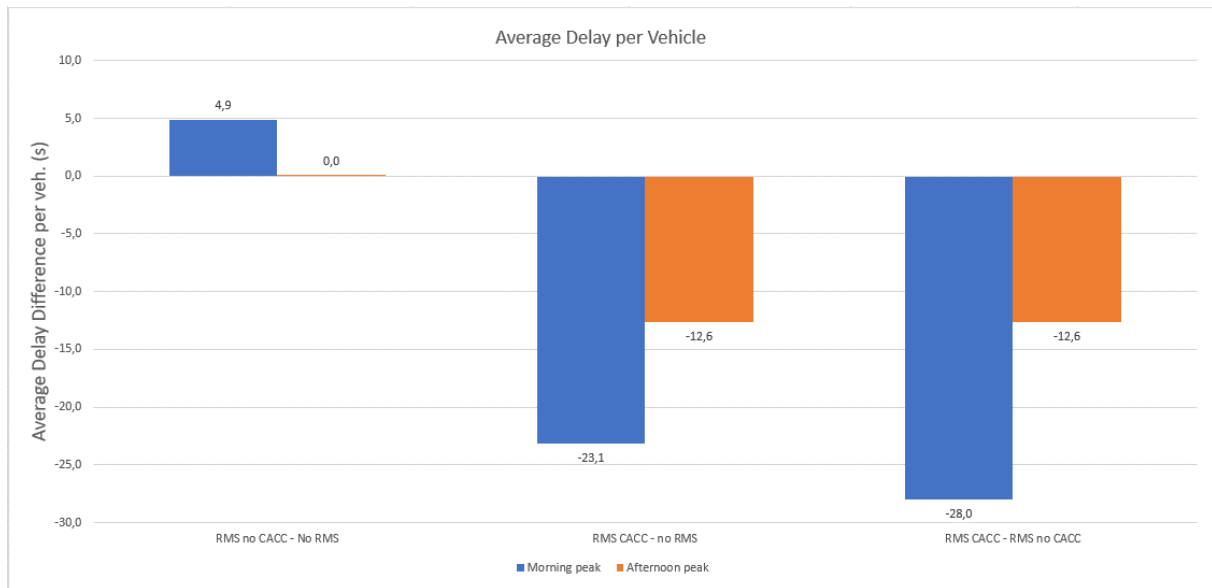Figure 29: Total Delay Savings (h) - Morning and Afternoon

Figure 30: Average Delay Savings per Vehicle (s)

These results have a similar trend to the results seen in the previous section, as shown in Table 22.

Table 22: Total Delay Change (%)

Change	*Morning*	*Afternoon*
2 – 1	+ 8 %	0%
3 – 1	- 39%	- 11%
3 – 2	- 43%	- 11%

The same effect between morning and afternoon peak is present here, indicating that the system's effectiveness in preventing delays is more pronounced when implemented prior to congestion. This observation can be attributed to the nonlinear nature of congestion, where even a minor increase in traffic volume can have a substantial impact on traffic flow, leading to rapid increases in delays. As the system is primarily designed to prevent congestion rather than resolve it, its impact is more pronounced during the morning peak when congestion is yet to fully develop.

4.7.2.4. AVERAGE SPEED

The system effects on average speed are considerably more inconsistent between scenarios and measurement points, as shown in Figure 31.
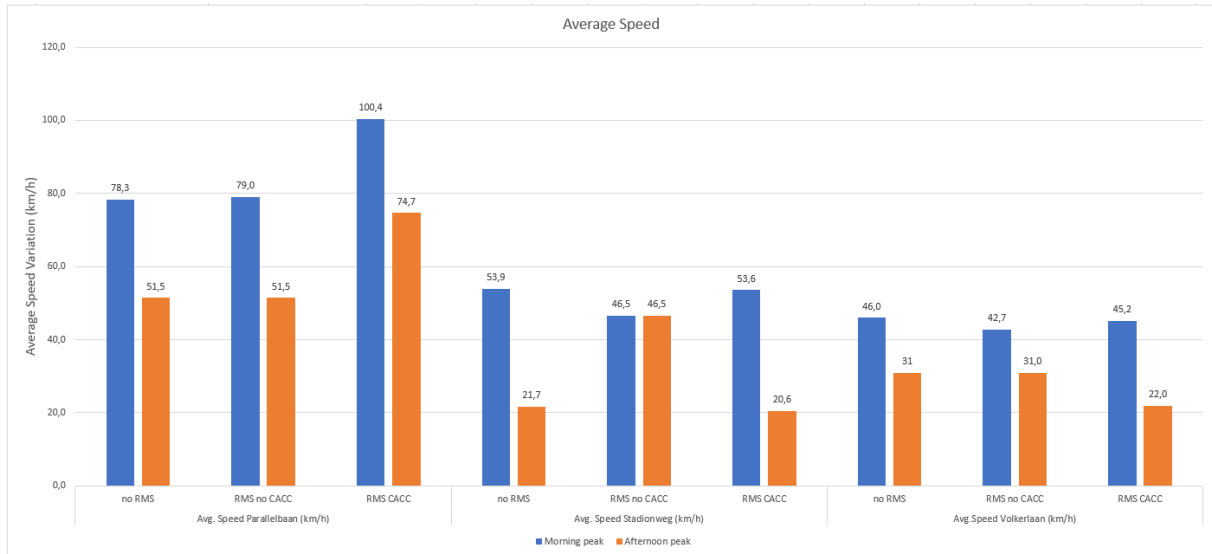
Figure 31: Average Speed Results (km/h) - Morning and Afternoon

This stems from various factors. Firstly, the system is designed to prioritise the performance of the mainline at the expense of the ramp, as this produces the biggest overall benefit for the network. This is evident when looking at the Stadionweg and Volkerlaan averages, as they show a decrease in speed when compared to the control scenario (Figure 32). The positive values when comparing the third and second scenarios are explained by the poor performance of that specific scenario.
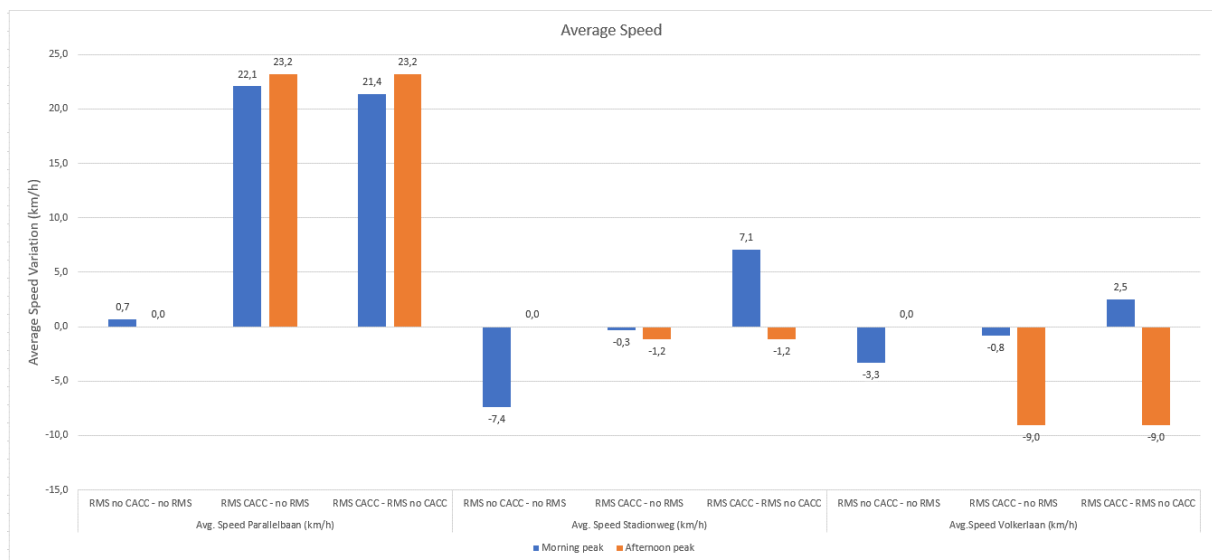

Figure 32: Average Speed Differentials by Scenario (km/h)

Secondly, afternoon performance is decidedly worse than the morning peak simulations. Like mentioned in section 4.6, this is expected as the traffic conditions are too degraded for the system to be as effective as the morning peak, where the strategy can mitigate or delay the onset of congestion.

Contrary to the previous sections, the increase is slightly higher during the afternoon peak when considering only the effects on the motorway. It should be mentioned that no scenario produced a decrease in motorway speeds.

4.8. DISCUSSION

The key findings drawn from this chapter are as follows, considering the third scenario of RMS with CACC:

1. Comparing to scenarios 1 and 2 respectively, the system led to reductions in total travel time of 25% and 28% in the morning, and 9% in the afternoon peak;

2. Total delay was reduced by 39% and 43% when compared to scenarios 1 and 2 respectively in the morning peak, and by 11% in the afternoon;

3. Motorway speeds improved by approximately 22 km/h during both peak times, compared to scenarios 1 and 2, albeit with a slight decrease in average ramp speeds.

These results indicate that the full strategy with CACC implementation produces an improvement in network performance compared with the base scenario. Though, simulations of the RMS without CACC scenario have produced a decrease in performance when compared to the same scenario.

Another important discovery is the difference between morning and afternoon performance, as the system is significantly more effective during the morning. This is due to the system being designed to prevent or delay the onset of congestion instead of resolving it. During the morning peak, as the conditions are not too degraded the strategy is more effective in comparison to the afternoon peak, where congestion is already present, which limits the system's performance.

Average speeds on the motorway are improved at a slight cost to the ramp speeds since the system prioritises motorway performance over the ramp.

These results build on evidence from previous studies that these systems are capable of producing a network benefit, with the contribution of this research being the evaluation of a cooperative strategy integrating these systems.

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CONCLUSION

In this dissertation, the primary objective was to identify and develop a control strategy to optimize the performance of existing ramp metering systems on motorways. The second objective was to evaluate the performance of such a strategy based on key performance indicators. To do so, two main research questions were formulated:

1. *How can an RMS control strategy that integrates gap detection and CACC be designed and implemented?*

2. *Would such a system be beneficial in terms of network performance?*

To answer the first question, a control strategy was devised in the third chapter that incorporates these systems into a cooperative algorithm, and successfully implemented in the case study of Rotterdam.

To answer the second research question, the main conclusions drawn from the simulations should be analysed:

1. Comparing to scenarios 1 and 2 respectively, the system led to reductions in total travel time in both the morning and afternoon peak, with the effect significantly more noticeable in the morning;

2. Total delay showed a similar trend as total travel time with drastic reductions when using the RMS with CACC in the morning peak, with a lower effect in the afternoon;

3. Motorway speeds increased by approximately 22 km/h during both peak times, compared to scenarios 1 and 2 with a slight decrease in average ramp speeds, which is expected as the system prioritizes motorway performance over the ramp.

The results of the simulations exhibit significant improvements in network performance when using the developed system, compared to the control scenario and the RMS scenario with gap detection alone. It can be concluded then that the system is beneficial in terms of network performance.

This research has provided valuable insights into the capabilities and limitations of the developed strategy in integrating gap detection and CACC in a cooperative ramp metering system. The findings of this thesis align with previous research, further supporting the notion that combining these technologies can yield substantial benefits in terms of traffic efficiency and safety.

However, it is important to acknowledge the limitations of this research in interpreting the results. Firstly, the network was simplified by anticipating the merging of the two ramp entry points, which does not accurately represent the real network. This was done in order to avoid additional complexity in merge timing and priority assignment, but future research should adapt the algorithm to account for these factors.

Methodological limitations were also present in this research. The suitability of the location was found to be lacking due to sub-optimal data, as it was measured detector data observed during congestion. However, time and guideline restraints made it unfeasible to modify said location. It is recommended other locations with better quality origin-destination data to be studied in the future.

Secondly, the assumption of 100% CACC adoption is unrealistic for the foreseeable future. A recommendation for future research is to expand the simulation study to include multiple adoption levels, to quantify the required adoption rate for a performance benefit.

Additionally, the number of parameter optimization and scenario testing runs were limited due to time constraints, and standard Wiedemann parameters were used. It is recommended to calibrate these parameters and conduct more simulations to gain a better understanding of the system's performance.

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