Evaluating Standstill Detection Systems

A quantitative and qualitative evaluation of standstill detections systems

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Challenge the future

"It does not matter how slowly you go as long as you do not stop."

— Confucius

Master Thesis

Evaluating Standstill Detection Systems
A quantitative and qualitative evaluation of standstill detection systems

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Preface

Witteveen+Bos, an international operating consultancy and engineering company, offered me an internship to conduct my MSc thesis. This thesis serves as the final step of study at the Technical University of Delft for the 3TU master program 'Construction Management and Engineering'.

Although this subject regarding traffic modelling, flow, and safety, was initially outside of my comfort zone, with the help of the people at Witteveen+Bos I was able to get a good grasp of the theory and the software tools. Furthermore, I would like to thank everybody; both colleagues and interns, in Almere and The Hague for making me feel welcome. Jan Willem and Aries; thank you for always being ready to answer all my questions on the principles of traffic flow and its simulation. And especially Robin, my supervisor, for always being helpful, finding the time for discussions, and your on-going support.

My gratitude also goes out to the rest of my thesis committee. Victor for: your guidance, working out the complicated model, and helping to understand the data analysis. Jos for having the amazing gift of no matter how bad I felt, making me leave every meeting with renewed hope. Finally thanks to Serge for his expertise, knowledge and critiques throughout this thesis.

For all the interviews I would like to thank the people at Rijkswaterstaat, Traffic Centres and the Provinces.

Finally I would like to thank my parents, family, and friends for never giving up on me and constantly asking me when I would (finally) finish my thesis.

Gyasi Johnson,
February 2014

Summary

Throughout the Netherlands, multiple traffic control centres are responsible for monitoring and influencing traffic on the Dutch freeways. A tool at the disposal of the traffic controllers is the Motorway Traffic Management (MTM) system. The MTM system allows traffic controllers to influence the traffic through the variable message signs (VMS). A subset of the MTM systems is the Automatic Incident Detection, which warns vehicles of unexpected traffic build up, i.e. congestion. To increase the control traffic centres can exert on traffic flow and safety, so called standstill detection systems can be implemented additional to the MTM and AID system. Standstill detection systems are capable of warning traffic controllers when individual vehicle speeds are below a predetermined threshold. The standstill detection systems are designed to respond faster than the already in place AID system. Due to the extra costs related to the standstill detection systems, it is not economically viable to implement these systems throughout the whole network. Therefore, the implementation of the standstill detection systems is focussed on traffic scenarios where blockades greatly influence the traffic, e.g. segments without hard shoulders. For this study, the focus is on: bridges, tunnels, and hard shoulder running lanes.

Currently, most detection systems are implemented with inductive loops; a well-known detection solution. Other solutions capable of standstill detection are:

- infrared,
- radar,
- Video Image Processing (VIP).

Although the utility of the standstill detection systems is not disputed, there have been no detailed studies into the relation between: costs, functionality, and the influence of a specific system on traffic flow and safety.

In other studies, detection systems are compared and evaluated on the following factors: error ratios, influence by external factors, installation methods, and unit costs. In their comparison, the relations between: costs, detection method, and the detection time of the various systems are not included. Hence, knowledge on the aforementioned relations is currently lacking. An explanation for this lack of knowledge is that system detection times cannot be derived from current available traffic data. The current data is incomplete, seeing as only the time of detection is registered, rather than the point in time the incident occurs.

To fill the gap of knowledge on the relation between: costs, functionality, and the influence of a specific system on traffic flow and safety, the following research question is chosen:

What is the relation between: cost, functionality, and the influence on traffic flow and safety, for the various, on-the-shelves market available, detection systems and what recommendations can be made per traffic scenario?"

In general, two specific categories of standstill detection methods can be distinguished; point detection and zone detection. A point detection system only detects vehicles directly above or below the detection point. Due to this detection method, the system is more likely to detect the congestion occurring due to the incident, rather than detecting the incident itself. The corresponding detection time of the point detectors is therefore related to the distance between the detection points of the system. Zone detection systems detect all vehicles in a stretched detection zone with a single detector. As opposed to the point detection system, zone detection systems can directly detect the incident vehicle and do not rely on the build-up due to the incident.

By creating a set of criteria, distilled from literature and stakeholder interviews, the standstill detection systems are evaluated. The criteria are divided into four main categories: functionality, costs, traffic flow, and traffic safety.

To give insight into the relation between detection method (point vs. zone detection) and the effects on traffic safety and flow, a model is developed. To simulate this model, the microsimulation program VISSIM is used in combination with a self-developed, Matlab controlled, COM interface. The COM interface makes it possible to incorporate the various dynamic processes present at incident locations. Such processes include, but are not limited to: dynamic speed limits, increased headway choice, and lane closures.

The microsimulation model simulates different flow rates and incident locations. For the flow rates, different flow-capacity (I/C) ratios (0.7, 0.8, and 0.9) are simulated. The different incident locations are simulated at 100m, 300m, or 500m downstream of the nearest MTM VMS. The created model provides data on: detection times, unwarned vehicles, undetected vehicles, queue lengths, queue growth speeds, discharge rates, delay, Time to Collision (TTC), and deceleration rates.

To assess aspects of the systems that cannot be modelled, additional criteria are used. These criteria include: traffic data collection, data accuracy, external influences, and their equivalent annual costs. For the evaluation of these criteria, a decision flow chart is followed and applied to three traffic situations: tunnels, bridges, and hard shoulder running lanes. The flowchart is applied for current on-the-shelf available detector systems in the Netherlands: inductive loops, passive and active infrared, radar, and VIP.

The results from the microsimulation model, on traffic flow and safety indicators, did not show significant differences when tested with a student t-test. The lack of significant differences is due to two main reasons: the high levels of variations in the simulation results, and the chosen high I/C ratios. The high flow rates are responsible for small differences in detection times. The maximum difference in the median system detection times, between the zone detection systems and point detector systems, is found at 41 seconds; comprising only 3% of the total incident duration of 1500 seconds. Due to the lack of significant differences, it is not possible to create concrete recommendations, for high I/C ratios, based on the model results.

By modelling lower flow rates, it is confirmed that the high flow rates are responsible for the lack of differences between the zone and point detection systems. Although only the detection times are modelled for lower I/C ratios, it shows a direct correlation between the detection times and I/C ratios. The results show that for lower I/C ratios, the differences between the detection methods appear to increase exponentially. Furthermore, the results show that, at higher spacing distances

between detector points, the exponential increase in detection time occurs sooner, i.e. at higher I/C ratios.

The analysis of the various detection systems, through the flow chart, indicates that VIP detection systems potentially have the best cost-functionality ratio. However, the VIP systems have an inherent weakness of being vulnerable to weather conditions. The low cost-functionality ratio is explained by the lower equivalent annual cost when compared to point detection systems. This lower equivalent annual cost is due to the higher range of detection, meaning fewer detectors are needed per length of freeway. To give an overview of the functionality of the various systems per traffic scenario a score sheet is created. This developed score sheet is meant as a tool for decision makers when selecting the appropriate detection system.

For future, model based, research on standstill detection systems, a set of recommendations is formulated. Firstly, to increase the validity of future microsimulation models, the following recommendations are made:

Researching all safety and flow indicators at lower flow levels, researching driver behaviour during the first initial seconds after the incident, a more intensive calibration, researching the time it takes for drivers to notify authorities, and the possibility of using multiple systems (data fusion). Secondly, for practical applications of the research, the following recommendations are created: placing detector points asymmetrically, i.e. placing fewer detector points in the left lane, and decision makers should be made well aware of the found relations between I/C ratios and the detection time.

Samenvatting

In Nederland zijn meerdere verkeerscentrales zijn voor het toezicht op, en het beïnvloeden van, het verkeer op de Nederlandse snelwegen. Om het verkeer te beïnvloeden hebben verkeersleiders meerdere instrumenten tot hun beschikken, één daarvan is het Motorway Traffic Management (MTM) systeem. Het MTM systeem geeft de verkeersleiders de mogelijkheid om het verkeer te beïnvloeden via de Variable Message Signs, e.g. de matrix borden. Een onderdeel van het MTM systeem is het Automatic Incident Detectie (AID) algoritme dat weggebruikers waarschuwt voor filestaarten. Om de informatiestroom naar de verkeersleiders te vergroten, zodat zij meer controle hebben op de verkeersdoorstroming en veiligheid, kunnen er stilstand detectiesystemen worden geïmplementeerd. Stilstand detectie systemen waarschuwen de verkeersleiders bij individuele voertuigsnelheden lager dan de ingestelde drempelwaarde. De systemen worden zo ontworpen dat deze sneller kunnen detecteren dan het AID algoritme.

Vanwege de extra kosten die het implementeren van deze stilstand detectie systemen met zich meebrengt, is het niet economisch rendabel om de systemen in het gehele netwerken te implementeren. Hierdoor wordt de implementatie van de stilstand detectie systemen beperkt tot verkeer situaties waarbij stilstaande voertuigen grote gevolgen hebben voor het verkeer, e.g. situaties zonder vluchtstrook. Voor dit onderzoek ligt de focus op: bruggen, tunnels, en spitsstroken.
Tegenwoordig zijn de meeste detectie systemen uitgevoerd met inductie lussen aangezien dit een vertrouwde oplossing is. Er zijn echter ook andere systemen die stilstand kunnen detecteren, zoals:

- Radar
- Infrarood
- Video Image Processing (VIP)

Hoewel er geen discussie is over de noodzaak van de stilstand detectie systemen, is er geen gedetailleerde studie geweest naar de relatie tussen: kosten, functionaliteit, en de invloed van een specifiek systeem op de verkeersdoorstroming en veiligheid.
In andere studies worden de detectiesystemen vergeleken en geëvalueerd op: fout marges, beïnvloeding door externe factoren, installatie methode, en de kosten per eenheid. Bij deze vergelijking wordt er niet gekeken naar de relatie tussen de kosten, detectie methodes, en de snelheid van detectie. Hierdoor mist er kennis over de eerder genoemde relatie van kosten en functionaliteit. Een van de redenen voor dit gebrek aan kennis is omdat de detectie tijden niet kunnen worden afgeleid uit de momenteel beschikbare verkeersgegevens. De huidige gegevens zijn onvolledig aangezien alleen het moment van detectie wordt geregistreerd, niet het moment van het daadwerkelijke incident.
Om meer inzicht te creëren in de relatie tussen kosten, functionaliteit, en de invloed van een systeem keuze op de doorstroming, is de volgende onderzoeksvraag geformuleerd:

Wat is de relatie tussen kosten, functionaliteit, en de invloed op de verkeersdoorstroming en veiligheid voor de verschillende commercieel beschikbare detectie systemen, en welke aanbevelingen kunnen er gedaan worden per verkeerssituatie?

Er kunnen twee specifieke categorieën stilstand detectiemethoden worden onderscheiden, punt detectie en zone detectie. Een punt detectie systeem detecteert alleen voertuigen direct boven of onder het detectiepunt. Door deze detectiemethode zal het systeem waarschijnlijker de congestie detecteren die optreedt door het incident dan het incident zelf. De detectietijd van de punt detectie systemen zijn hierdoor gerelateerd aan op de afstand tussen de detectiepunten van het systeem. Zone detectiesystemen detecteren alle voertuigen in een uitgestrekte detectiezone met één detector. In tegenstelling tot de punt detectiesystemen kan een zone detectiesysteem het incident direct detecteren en is dus niet afhankelijk van congestie die vormt achter het incident.

Door het creëren van een reeks criteria, gedestilleerd uit literatuur en interviews met stakeholders, worden de stilstand detectiesystemen geëvalueerd. De criteria zijn onderverdeeld in vier categorieën: functionaliteit, kosten, verkeersdoorstroming en verkeersveiligheid.
Om de verschillen te onderzoeken tussen de twee detectiemethoden, punt en zone detectie, is een model ontwikkeld. In dit model worden de effecten van de twee verschillende detectie methoden op de verkeersdoorstroming en veiligheid onderzocht. Om dit model te simuleren is er gebruik gemaakt van het micro simulatieprogramma VISSIM in combinatie met een zelf ontwikkeld, Matlab aangestuurd, COM interface. Via deze COM interface is het mogelijk de verscheidene dynamische processen, aanwezig bij incidenten, toe te voegen aan het model. Deze processen includeren, maar zijn niet beperkt tot: dynamische snelheidslimieten, het veranderen van de headway keuze, en het afkruisen van rijstroken.

Het micro simulatiemodel simuleert verschillende intensiteiten en incident locaties. Ten eerste zijn er drie verschillende intensiteit – capaciteit (I/C) verhoudingen (0,7; 0,8 en 0,9) gesimuleerd. Ten tweede zijn er drie verschillende incident locaties gesimuleerd op 100, 300, en 500 meter stroomafwaarts van het dichtstbijzijnde matrix bord. Uit het micro simulatie model zijn gegevens beschikbaar over: detectie tijden, aantal niet gewaarschuwde voertuigen, aantal niet gedetecteerde voertuigen, file lengtes, de snelheid waarmee een file groeit, doorstroming, totale vertraging, Time to Collision (TTC) en acceleratie deceleratie.

De gevonden criteria die niet kunnen worden gemodelleerd in het simulatie programma worden kwalitatief beoordeeld. Deze criteria zijn: data collectie mogelijkheden, nauwkeurigheid van de gegevens, beïnvloeding door externe invloeden en de Equivalent Annual Costs (EAC) van de systemen. Deze criteria worden geëvalueerd aan de hand van een besluitdiagram en toegepast op de drie verkeersituaties tunnels, bruggen en spitsstroken. Dit wordt toegepast op de huidige commercieel beschikbare detectie systemen in Nederland: inductielussen, passief- en actief infrarood, radar en VIP systemen.

De resultaten van het micro simulatie model, kijkend naar doorstromings- en veiligheidsindicatoren, geven geen significante verschillen aan tussen de systemen. Om dit aan te tonen is er gebruik gemaakt van de Student t-toets. Het ontbreken van de significante verschillen tussen de systemen heeft twee redenen: de hoge variatie in de simulatieresultaten en de gekozen hoge I/C ratio's. Door de hoge gesimuleerde intensiteiten zijn er slechts kleine verschillen in de detectie tijden. Het grootste verschil in de mediane systeem detectie tijden, tussen de zone detectie systemen en de punt detectie systemen is 41 seconden. Deze 41 seconden zijn slechts 3% van de totale incident duur van omstreeks 1500 seconden. Omdat er geen significante verschillen zijn tussen de detectie systemen, is het niet mogelijk concrete aanbevelingen te maken voor de hoge I/C ratio's op basis van de modelresultaten.

Door het simuleren van I/C ratio's wordt bevestigd dat de hoge intensiteiten verantwoordelijk zijn voor het gebrek aan significante verschillen tussen de punt en zone detectiesystemen. Hoewel er alleen resultaten zijn betreffende de detectietijden toont het model een duidelijke relatie aan tussen de detectie tijden en de I/C ratio's. De resultaten tonen aan dat de verschillen tussen de punt en zone detectie tijden exponentieel toe lijken te nemen. Dit exponentiele verschil tussen de detectie methoden bij lagere I/C ratio's treedt eerder op naarmate de afstanden tussen de punt detector punten toeneemt.

De evaluatie van de verschillende systemen door middel van het besluitdiagram geeft aan dat VIP detectie systemen potentieel de beste kosten/functionaliteit verhouding hebben. De VIP systemen hebben echter een inherente kwetsbaarheid voor externe factoren. De lage kosten/functionaliteit verhouding komt door de lagere equivalente jaarlijkse kosten in vergelijking met de punt detectie systemen. Deze lagere jaarlijkse kosten komen door het grote detectiegebied, waardoor er minder detectoren nodig zijn per lengte eenheid van de snelweg. Om een overzicht te verschaffen van de functionaliteit van de verschillende systemen per verkeerssituatie is een scoreblad ingevuld. Dit scoreblad is bedoeld als hulpmiddel voor beleidsmakers bij het selecteren van het gepaste detectie systeem.

Voor toekomstige, model gebaseerd, onderzoek naar stilstand detectie zijn een reeks aanbevelingen geformuleerd. Ten eerste, om de validiteit van toekomstige simulatiemodellen te verhogen zijn de volgende aanbevelingen geformuleerd:

- Alle doorstromings- en veiligheidsindicatoren simuleren op lagere I/C ratio's.
- Het onderzoeken van het gedrag van bestuurder tijdens de eerste initiale seconden na het incident.
- Het onderzoeken van de tijd die, bij het incident betrokken, bestuurders nodig hebben om de gepaste autoriteiten te contacteren
- Het gebruiken van meerdere data bronnen (data fusie)

Ten tweede zijn de volgende aanbevelingen geformuleerd voor praktische implementatie van dit onderzoek:

- Het asymmetrisch plaatsen van detector punten, i.e. het plaatsen van minder detector punten in de linker rijstrook
- Het bewust worden bij beleidsmakers van de relatie tussen de detectietijden en de I/C ratio's.

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Glossary and Abbreviations

The following definitions and abbreviations are used throughout the thesis.

Definitions	Meaning
MTM	Motorway Traffic
VMS	Variable Message Sign
AID	Automatic Incident Detection
IM	Incident Management
VIP	Video Image Processing
I/C	Flow / Capacity ratio, from the Dutch "Intensiteit / Capiciteit"
Pce/h	Personal Car Equivalent per hour
Veh/h	Vehicles per hour
EAC	Equivalent Annual Cost

Notation

The following variables are used throughout the thesis.

Symbol	Meaning
$\bar{h}$	Mean time headway
h_i	Time headway vehicle i
T	Period of time (years or seconds)
n	Number of vehicles
q	Flow
u	Speed
k	Density
C	Capacity
C_{pce}	Capacity in pce/h
Pce	Personal Car Equivalent
C_{veh}	Capacity in veh/h
D	Demand
I/C	Flow / Capacity Ratio
ω	Shockwave speed
f_{pae}	Pce factor for HGV
$\%_{ft}$	Percentage of HGV
x_i	Position vehicle i
L_i	Length vehicle i
v_i	Speed vehicle i

ζ_0	Point in time when vehicle i enters the network
ζ_T	Point in time when vehicle i leaves the network
τ_{sc}	Time interval
T_{span}	Lifespan of asset
C_t	Costs in year t
r	Discount rate
$C_{maintenance}$	Annual maintenance costs
CC0….CC9	VISSIM calibration parameters
N	Amount of required runs
n_1	Number of initial runs
ε	Confidence factor
$\bar{X}(n_1)$	Mean of initial runs
h_1	Variation of initial run
$t_{n_1-1;\alpha}$	t-value for confidence level α
σ^2	Variance of initial run
F	Capacity factor

1

Introduction

This first chapter serves as an introduction into: the research subject, the problem definition, and the practical value of this research. Next the outline of the research is presented. Paragraph 1.3 formulates the objective of the research, paragraph 1.4 presents the research questions used throughout the research. Paragraph 1.5 gives an insight into the research methods and research boundaries; finally paragraph 1.6 offers a list of assumptions and boundaries applied for the research. The goal at the end of this chapter is to provide: a clear definition of: the subject, the problem definition, and an insight into the overall processes that will be followed throughout the research.

1.1 Background

In today's society transportation has become an increasingly important aspect of the economy. As society keeps growing, the roads are used more intensively, leading to a higher density of traffic. This highest density leads to a higher need for information to sustain the traffic safety and flow. Long-term collected data, such as the MoniCa data used by Rijkswaterstaat, gives insights into important congestion points and provides vital information surrounding: volumes, speeds, congestions, and other useful data for infrastructural planning. A recent example is the use of the gathered MoniCa data in order to assess the effects of implementing the new increased maximum speeds (Rijkswaterstaat, 2011).

Besides the collection of MoniCa data, it is also very useful to gather and use traffic flow data in real time. By monitoring real time gathered information, traffic mitigations can be initiated to increase traffic safety or flow. An example is the use of the Motorway Traffic Management (MTM) system by Rijkswaterstaat, which detects congestions and uses variable message signs (VMS), i.e. matrix signs visible to all drivers above or next to the roads. With the use of the MTM system the traffic centres can: lower the speed limit, warn upcoming vehicles, or close of lanes for traffic.

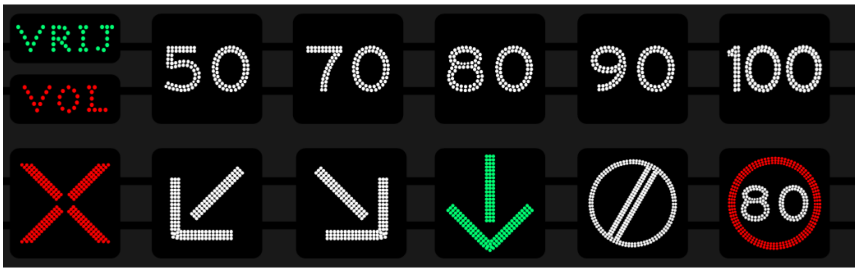

Figure 1: Matrix Signal

The detection of incidents and traffic build up is supported by the already implemented AID (Automatic Incident Detection) system, integrated within the MTM system. The AID system calculates the moving average of the traffic per lane and automatically implements mitigations through the VMS. To determine the presence of an incident or congestion, the AID system calculates the moving average speed of multiple vehicles. The moving averages are calculated from data supplied by induction loops which are also used to gather the MoniCa data. Traditionally, the average distance between these detection points is around 500 meters. Due to the relative high distances between detection points, it is most likely the AID does not detect the incident directly, but detects the congestion formed due to the incident. However, it is also possible to directly detect incidents that form a hazard to the traffic flow and safety, instead of detecting the congestion that follows from the obstruction**.** This is possible by using roadside standstill detection systems that measure individual speeds of vehicles. Unlike the AID system, these systems give a warning when individual vehicles are below the speed threshold; leading to faster detection of incidents.

Currently, most of the data collection is done by using: induction loops embedded into the road surface, cameras with video analysis software, human (camera) observations, radar, or infrared technology. These systems detect vehicles that pass over the detection points or vehicles that pass through the zone of detection. By processing the collected data with algorithms, characteristic values of the traffic can be derived, e.g. vehicle category, direction, and speed. The collected data is transmitted to a traffic centre controller, who applies the appropriate interventions provided by the Incident Management (IM) directive implemented by Rijkswaterstaat (Rijkswaterstaat, 2012a).

To improve the system’s ability to quickly detect incidents, the standstill detection systems use smaller intervals between detection points compared to the AID system. Decreasing the interval distance leads to higher costs. Due to the extra costs related to the standstill detection systems, it is not economically viable to implement these systems throughout the whole network. Hence, the systems are not applied throughout the whole infrastructure network in the Netherlands, but are limited to situations that require the extra level of safety.

1.2 Problem Definition

Although the utility of the standstill detection systems is not disputed, there have been no detailed studies into the relation between: costs, functionality, and the influence of a specific system on traffic flow and safety. Until now there have been studies researching: the types of algorithms that can be used in combination with induction loops (van de Ven, 2007) , the characteristics of the different detection systems (Martin, 2003), and the effects Incident Management on traffic flow and safety.

Although these studies give an accurate description of how these systems work and which set of software/algorithm is best suited for the various systems, none of these studies give an insight into the relation between costs and functionality in regards to incident detection.

As inductive loops have been the main method of detection for many years, they have been the subject of many studies. However, there is limited research into the functionality of the systems regarding the appropriate distances between detector loops. In the studies on algorithms, the various algorithms are judged based on: speed of detection, detection accuracy, and number of error measurements. The speed of the algorithms is judged based on their capability to quickly detect an incident from the available data. Because the data does not specify the time an incident occurs, the initial time it takes the system to detect the incident, i.e. the system detection time, cannot be calculated. With inductive loops, the distance between loop pairs and thus the number of detectors, determines to a great extent the detection time of incidents. Placing more detectors means faster detection, but inherently leads to more costs and higher system complexity. The described relation between the interval distance of the loops and the system detection time is not limited to inductive loops; it applies to all systems using fixed detection points.

In studies that compare various standstill detection systems, the systems are evaluated, among others, based on: error ratios, external factor influence, and unit costs. In their comparison of costs, the relation between detection zones and system detection times is not included. Therefore, some knowledge on the relation between costs and functionality is lacking.

To get an insight into the system detection time, and the systems' effects on traffic flow and safety, it is necessary to be able to control the conditions of the incident. To circumvent experimenting with incidents on a freeway, deemed as non-practical, incidents can be simulated with a traffic simulation program, provided adaptations are applied to the standard software. By simulating an incident with various detection set ups, this research will try to determine the effects of the various systems on traffic flow and safety; creating the opportunity to create a link between functionality and cost of the various detection systems.

1.3 Research Objective

As explained in paragraph 1.1 and 1.2, there is a lack of a clear understanding between the functionality, costs, and the effects on traffic flow and safety for the various detection systems. This study tries to address these issues by setting the following research objective:

Giving insights into the relation between: cost; functionality; and the influence on traffic flow and safety, and provide recommendations based on various traffic scenarios
by
Analysing the effects of the various standstill detection system characteristics, on traffic flow and safety, in a traffic simulation model and evaluating the effects of the various systems in relation to their Life Cycle Costs.

1.4 Research Questions

In order to reach the research objective several research questions are derived. These questions are the red-line throughout the research. Each central question has a set of sub-questions. In the end, if all sub-questions are correctly answered, the combined answers should answer the central question.

Research Question 1:

> "Which requirements and/or needs are put on the use of the standstill detection systems, per traffic scenario, by the different stakeholders and regulations?"

Sub questions:

- Which stakeholders can be defined for the detection systems?
- Which traffic situations need standstill detection systems, and which do not?
- What requirements are set on standstill detection systems?

Research Question 2:

> "Which theories on traffic flow and safety, in relation to incidents and congestion, are relevant to standstill detection, and can these be translated and evaluated in a traffic simulation model?"

Sub questions:

- Which indicators give an insight into the performance of the standstill detection systems?
- Which simulation model is suitable to simulate the effects of incidents?
- Which indicators can be evaluated in the simulation model?
- Which processes occur at incident locations?
- What are the effects of incidents on traffic flow and safety in the model?

Research Question 3:

> "What are the relevant system characteristics of the various standstill detection systems?"

Sub questions:

- Which systems are capable of stand still detection and are commonly used in the Netherlands?
- What are the detection capabilities of the various standstill detection systems?
- What are the drawbacks of the various standstill detection systems?
- Which characteristics are relevant for standstill detection?
- What are the Life Cycle Costs per system?

Main Research Question:

> "What is the relation between: cost, functionality, and the influence on traffic flow and safety, for the various, on-the-shelves- market available, detection systems, and what recommendations can be made per traffic scenario?"

1.5 Research Method

By explaining the research model, this paragraph provides an insight into the research method used to answer the research questions. For this research the following approaches have been used:

- Literature study and interviews
- Calibrating the microsimulation model
- Adjusting the microsimulation model to simulate incidents
- Evaluating simulation data in Matlab
- Analysing standstill detection system characteristics.

The model gives a visual representation of the research process; it serves as the backbone of the research and provided a tool to monitor the progress throughout the research. Furthermore, the model can be used to explain the general outline of the experiment to external parties. The visual representation of the model can be seen below, followed by a textual explanation of the model and its components.

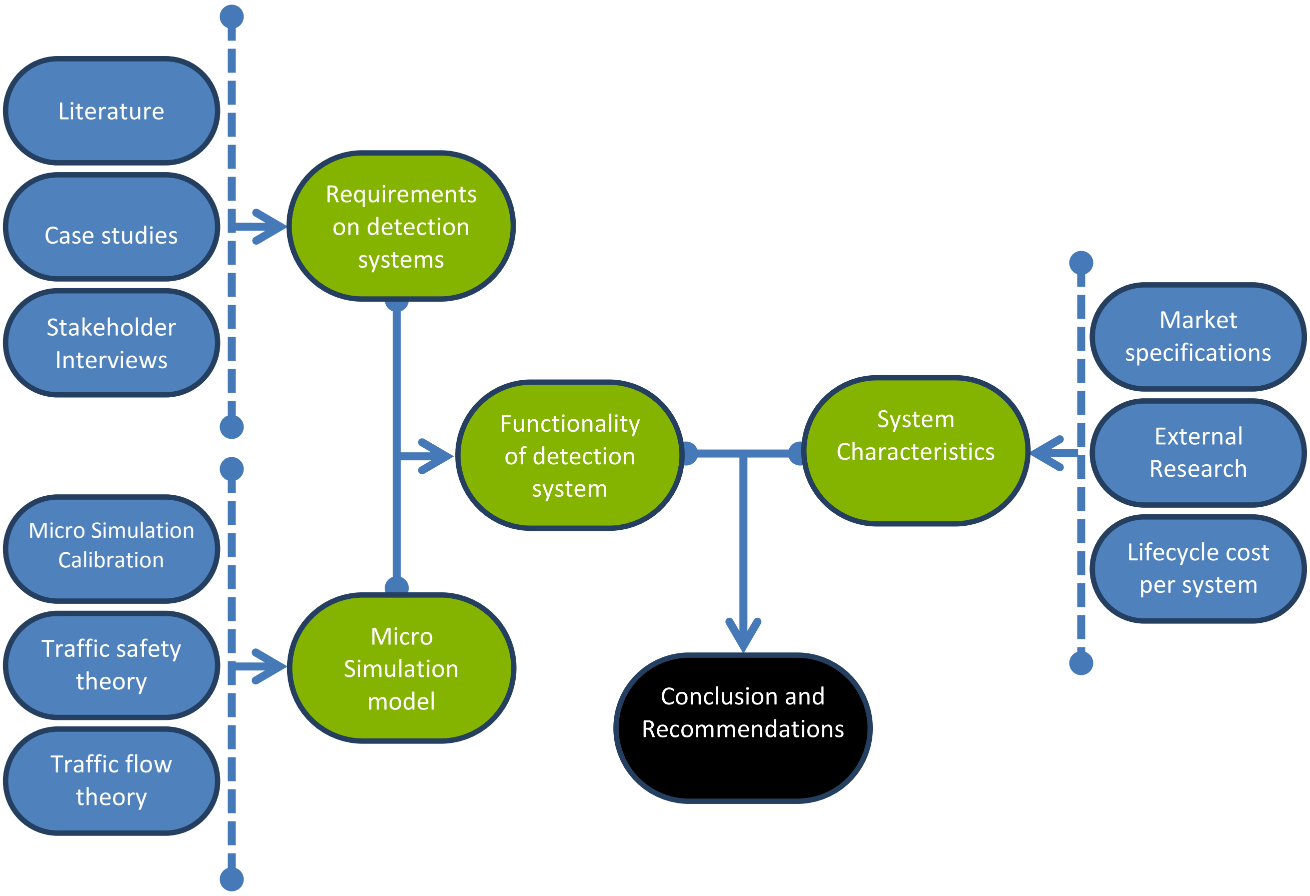

Figure 2: Research model

To determine which characteristics of standstill detection systems determine the functionality of the systems, a set of criteria will be derived. To derive the set of criteria, the following steps are taken: a literature study is performed, a case study is reviewed, and several interviews are conducted with stakeholders. Not all found criteria can be analysed in the microsimulation model. To determine which criteria can be simulated, the model is first created. To create the experimental incident setup, used in the microsimulation model, a calibration of the model is required. Traffic flow and safety theories are used to create the experimental model setup, and are used to evaluate the output of the model. To determine the characteristics of the various detection systems information is gathered from suppliers, literature and theory on life cycle costs. The characteristics that cannot be simulated in the microsimulation model will be evaluated qualitatively.

Finally, by combining the results from quantitative the microsimulation model and the qualitative evaluation, recommendations on detector choice are made per traffic scenario.

1.6 Research Boundaries and Assumptions

In order to constrain the boundaries of the research, it is important to narrow down the field of research.

Incident Management

The Incident Management (IM) applied by Rijkswaterstaat and the lower governments is displayed in *Figure 3*. This research will only experiment with the first phase of the incident management. Thus the research will not go into depth beyond the process that comes after the point of the incident detection, i.e. when comparing the various systems we assume that the handling of the incident after detection will be conducted identically for all systems. The times used per phase are presented in paragraph 4.2.2.

Figure 3: Phases of Incident Management

MTM Presence

The MTM system and its VMS, e.g. matrix signs are not present throughout the whole Dutch freeway network. However, as this thesis focuses on: tunnels, hard shoulder lane running, and bridges the presence of a MTM system is assumed.

Maximum detection time

When incidents occur on the freeway, it is assumed that the vehicles involved will have contacted the appropriate authorities within five minutes. This means that even if no detection occurs the incident will have been manually reported after 5 minutes, i.e. for the detection systems a maximum detection time of 300 seconds is applied. The value of 5 minutes was chosen after an initial interview with Cees v/d Pligt, Transition Manager of Traffic Control Centre Rhoon.

Considered Detector Systems

For this thesis the considered detector systems have been narrowed down; only current commonly used, on-the-shelf, systems available in the Netherlands are considered. Hence, this thesis has a viable maximum recommendation lifespan of approximately 15 years; after this time period the technology will have evolved beyond the currently applied detectors. In-car or other newly developed systems have not been considered; they are not considered as current on-the-shelf available detector systems. However, in the future these systems may prove to be the best available detector systems.

Considered Traffic Situations

The focus for this thesis is on 3-lane freeway situations without hard shoulders: tunnels, hard shoulder running, and bridges. This translates into situations in which there is no hard shoulder lane available to which vehicles can escape; incidents directly lower the available capacity of the freeway. As a consequence this thesis does not directly apply to ‘normal’ freeway situations in which hard shoulders are available.

Incident Location

In the microsimulation model incidents are simulated just upstream of a detector point. Realistically this will not occur during every incident. Because all incidents are simulated at the maximum distance of the first upstream detection point, the found detection times should be seen as an indication of the maximum detection times.

Terminology

In this thesis the microsimulation model is used to simulate the differences between point and zone detection systems. Throughout the thesis references will be made to the different systems. To avoid ambiguousness, the following definitions are proposed for the different setups of point detection systems.

- **25m detection system**, point detection systems with 25 meters between detector points.
- **50m detection system**, point detection systems with 50 meters between detector points.
- **100m detection system**, point detection systems with 100 meters between detector points.
- **MTM system,** detection system, detecting incidents through the AID algorithm, integrated in the MTM system.

1.7 Report Structure

The structure of this report is as follows:

- Chapter 2 provides an overview of all used theorem surrounding: traffic safety, traffic flow and detector algorithms. The chapter serves as the theoretical basis required throughout the continuation of the research.
- In chapter 3 an overview of the selected detection systems is presented. Along with the system a set of distilled requirements is provided, finally an overview of the used theory to calculate the lifecycle costs is provided.
- Chapter 4 serves as an insight into the: selection, calibration, creation, and adaptation of the microsimulation model.
- Chapter 5 is a summarisation of the found microsimulation results. For a raw overview of the model results, multiple tables are displayed in appendix A.
- In Chapter 6 the selected detection systems from chapter 3 are analysed for per traffic scenario. From the analysis of the detection systems, score sheets are created.
- Chapter 7 and 8 provide an overview of all found conclusions and offer recommendations.

2

Theoretical Background

This chapter serves as an overview of the theories required during the continuation of this thesis. Paragraph 2.1 gives an overview of the theories on traffic flow, required to calibrate and evaluate the microsimulation model. In paragraph 2.2 an overview is presented on the theory on traffic safety, used to evaluate the effects the various detection systems have on the traffic safety. Finally, paragraph 2.3 presents an overview of the currently available detection algorithms, from which the appropriate algorithms will be used in the microsimulation model.

2.1 Traffic Flow

The goal of this thesis is to create insights into the effects various standstill detection systems have on traffic flow and safety per traffic scenario. This paragraph serves as a brief introduction into the theories that are necessary to assess the different effects the standstill detection systems have on traffic flow. The goal of this paragraph is to provide an overview of relevant traffic flow theories and provide theoretical input for following chapters. For this paragraph the main source of information are the dictates of (Hoogendoorn, 2011).

Macroscopic - Microscopic

Before the various theories are discussed; first a division between macroscopic and microscopic analyses is made.

Macroscopic analyses look at the overall traffic flow. They do not describe individual cars, but rather describe the traffic flow as a whole. Macroscopic characteristics are: flow, density, time mean speed, and space-mean speed.

Microscopic analyses look at the behaviour of the individual driver; vehicles in the network are seen as individual objects instead of part of the overall flow. Microscopic characteristics are: time headways, individual speeds, and distance headways. The microscopic characteristics are used in the calibration of the microsimulation model; which is presented in chapter 4.1

Upstream and Downstream

To avoid ambiguities, a clear distinction is required between up- and downstream traffic. A distinction can be made when seeing traffic as a stream flowing from point A to B, passing a fictional measurement point. Vehicles that have not passed the measurement point are defined as upstream traffic; vehicles that have passed the measurement points are defined as downstream traffic. This is illustrated in *Figure 4*.

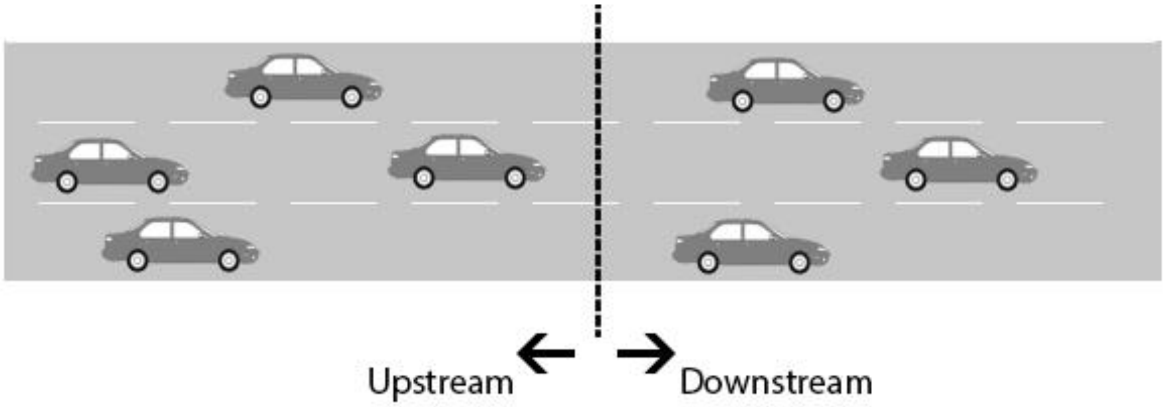

Figure 4: Up and Downstream traffic

2.1.1 Traffic Flow Variables

During the continuation of this thesis various traffic flow variables are used in order to evaluate or analyse aspects of the traffic. This paragraph serves as an interlude of the used variables.

Time Headway

Time headway is defined as the period of time between two passing vehicles (Hoogendoorn, 2011). A distinction can be made between the 'gross' time headway (or just time headway) and the 'nett' time headway. For the gross time headway the time is taken between the passing of both rear-ends of the vehicle, see *Figure 5*. The nett time headway is the time between the passing of the rear of the leading vehicle and the front of the following vehicle; the headway is not dependant of the length of the following vehicle (Hoogendoorn, 2011). The mean time headway can be found with the below equation. For the rest of the thesis the gross headway is referred to as headway.

$$\bar{h} = \frac{1}{n}\sum_{i=1}^{n} h_i = \frac{T}{n} \qquad (2.1)$$

Where:

n	=	Number of vehicles
T	=	period of time
h_i	=	time headway vehicle i
$\bar{h}$	=	mean time headway

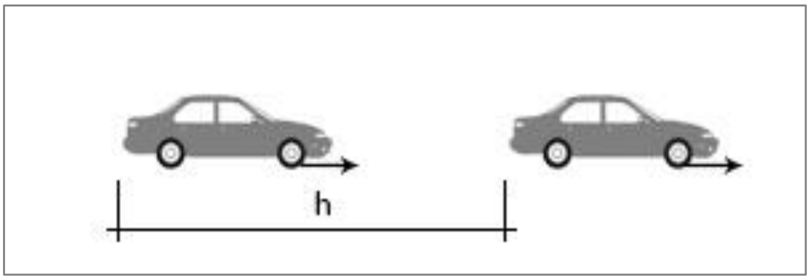

Figure 5: Time headway

Flow

The intensity or flow is defined as the number of vehicles passing a cross-section of a road per unit of time. The flow can be derived for multiple time periods, but most commonly a time period of one hour is taken. The flow can also be derived with the sum of time headways of the vehicles, leading to the following equation (Hoogendoorn, 2011).

$$q = \frac{n}{T} = \frac{n}{\sum_i h_i} = \frac{1}{\frac{1}{n}\sum_i h_i} = \frac{1}{\bar{h}} \qquad (2.2)$$

Where:

n	=	Number of vehicles
T	=	period of time
h_i	=	time headway vehicle i
$\bar{h}$	=	mean time headway

The above equation gives a direct relation between the headway and the flow, this is important when calibrating and using the microscopic simulation model.

2.1.2 Fundamental Diagrams

To describe the relations between the characteristics of macroscopic traffic flow, fundamental diagrams are used. These diagrams created with the following characteristics:

- Intensity - density $q = q(k)$
- Speed - density $u = u(k)$
- Speed - intensity $u = u(q)$

Note that all three of these diagrams display the same information and can be used to deduce the others.

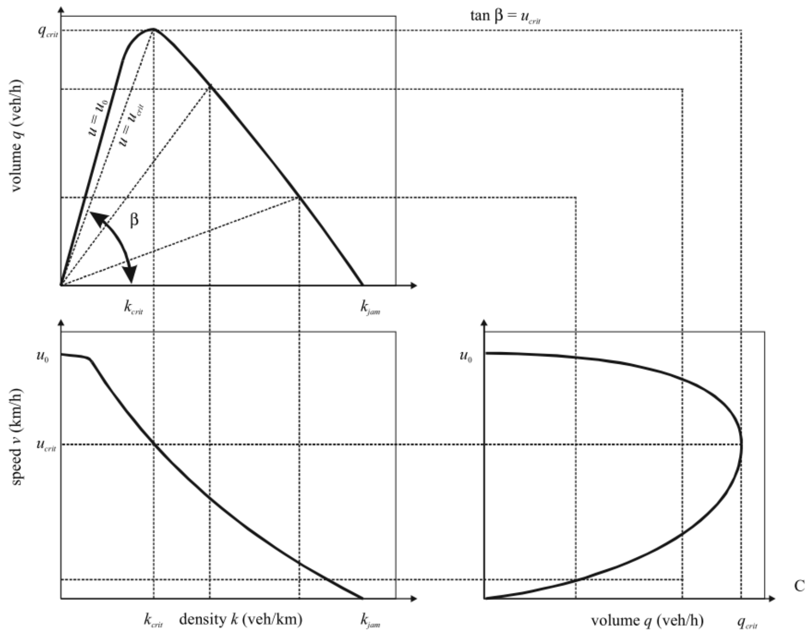

Figure 6: Interrelated forms of the fundamental diagram, (Hoogendoorn, 2011)

For the calibration of our model the Capacity q_c ; the maximal flow, also referred to as the critical flow is used.

Schematized Fundamental Diagram of Daganzo

When developing new models for traffic operations a fundamental diagram is required. The chosen model should be simple and correctly represent the essential properties of the traffic flow. Greenshields' model (Greenshields, 1934) is a fulfilling example for these requirements. (Daganzo, 1997) introduced an alternative in which the function $q(k)$ is represented by two straight lines and uses the three parameters: u_0 , k_c ,and k_j . Because Daganzo gives a simple but adequate fundamental diagram it is the chosen diagram for this thesis.

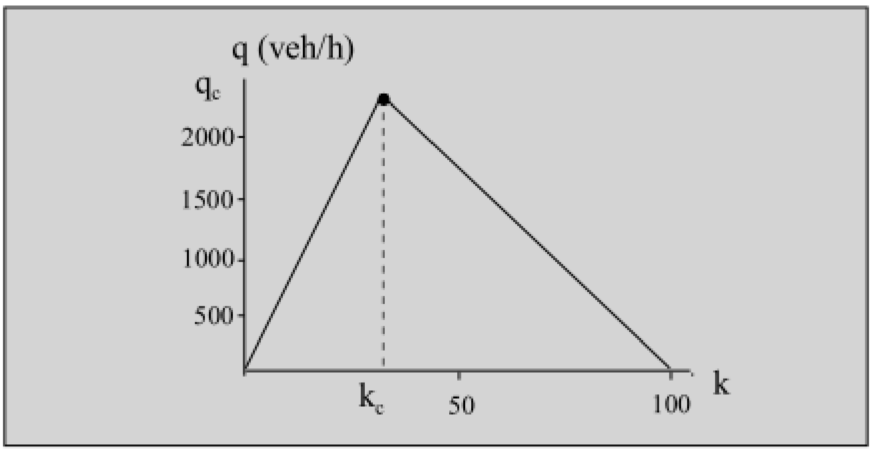

Figure 7: Daganzo 's fundamental diagram, (Hoogendoorn, 2011)

Discontinuous Diagram

After observations of traffic streams with increasing density, a notion of a discontinuing diagram was created by (Edie, 1965). The diagram uses the notion that a traffic stream with increasing density, starting from free or stable flow, can reach a higher flow than traffic streams starting from a congested state that end in the 'queue discharge capacity'. This is represented in the below figure and is called the 'capacity drop'. Typically this is around 10% (Cassidy & Bertini, 1999).
This capacity drop will be used in order to determine the maximum flow during the calibration of the simulation model in chapter 4.

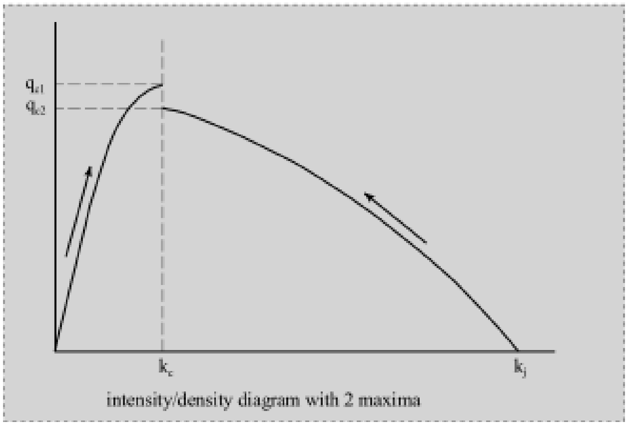

Figure 8: Fundamental diagram with a discontinuity, (Hoogendoorn, 2011)

2.1.3 Bottlenecks

A bottleneck is defined by a segment of road that has a lower level of capacity than the upstream segments (Hoogendoorn, 2011). For this thesis an occurred incident can be seen as a bottleneck as it leads to reduced capacities due to a blocked lane or other factors surrounding incidents. Some of the factors surrounding incidents are analysed in paragraph 4.2. An important aspect of the bottlenecks' capacity is whether or not the capacity is dropped below the current flow. As long as the demand does not exceed the capacity of the bottleneck there will be no effect on the flow of the traffic. In the bottleneck itself a small delay may occur due to higher densities, but congestion will not form. When the demand is higher than the capacity of the bottleneck, congestion will start forming upstream of the bottleneck. This is of importance when selecting the demand on the network, i.e. when choosing an input flow which is too low there will be no congestion which can be detected by the detection systems. The formed congestion will travel upstream due to the shockwave effect, which is explained in paragraph 2.1.6.

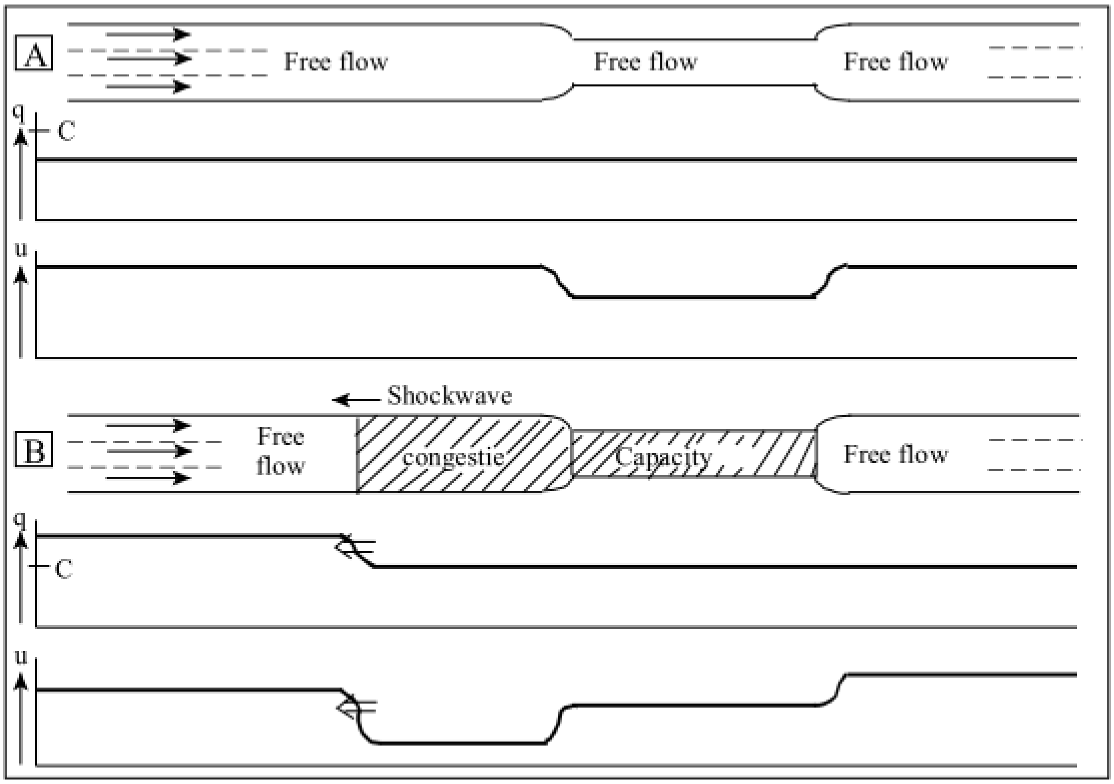

Figure 9: Effects of a Bottleneck, (Hoogendoorn, 2011)

2.1.4 Congestion and Delay

In Figure 10 two curves are displayed: the green line represents the departure curve, and the red line represents the arrival curve of a fictional road section. The slopes of the green and red line respectively represent: the capacity C and the demand D. When D becomes larger than C, congestion starts to form. The vertical distance between the departure and demand curve equals the length of the queue in number of vehicles. Note that in this diagram the vehicles are stacked vertically; therefore the diagram does not completely represent the reality. When D becomes smaller than C, the congestion has reached its maximum length and will start to diminish. The horizontal distance between the curves represents the delay for each vehicle and thus the surface between the curves equals the total delay. As the surface represents the total delay, it can be derived that the delay decreases if the duration of the oversaturation is shorter. In order to evaluate the delay data, provided by the microsimulation model, this diagram is used as the theoretical background, see paragraph 5.6.

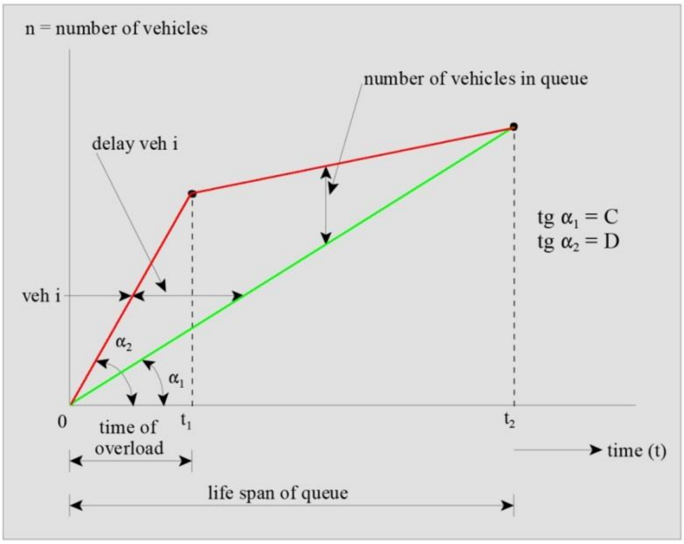

Figure 10: Queue forming, (Hoogendoorn, 2011)

2.1.5 I/C Ratios

According to Rijkswaterstaat the relation between the flow (I) and the capacity (C) gives an indication of the quality of traffic flow on a road segment. In the 'Capaciteitwaarden Infrastructuur Autosnelwegen' (CIA) document (Rijkswaterstaat DVS, 2011) proposes four different ratios. Note that the capacity (C) is the free capacity of the road segment.

I/C Ratio	Traffic Flow
I/C less than 0.8	Good traffic flow, without significant congestion forming (chance <<1%) with exception of incidents
I/C 0.8 - 0.9	Mediocre traffic flow with structural congestion forming. Congestion will not occur daily, but the traffic flow is sensitive to small disturbances.
I/C bigger than 0.9	Poor traffic flow. Structural daily congestion with regular stationary queues, the influence of disturbances is significant. Rain and incidents can double the factor of congestions.
I/C bigger than 1.0	Very poor traffic flow. Daily still standing congestion

Table 1: I/C Ratio overview

2.1.6 Shockwave Theory

Waves that can occur in traffic flow are categorised as either kinematic waves or shock waves. Shockwaves originate from a sudden and substantial change in the state of the traffic flow, i.e. a shockwave is defined by a discontinuity in the flow-density conditions in the time-space domain. The speed of the shockwave is calculated as follows.

$$\omega = \frac{q_i - q_j}{k_i - k_j} \tag{2.3}$$

According to (Hoogendoorn, 2011) with small changes in q and k, the above equation becomes $\omega = \frac{\partial Q}{\partial k} = c$; the kinematic wave is the limiting case of a shockwave. The maximum speed of the shockwave lies around the ~20 km/h when regarding real life traffic congestion (Sugiyama, 2008).

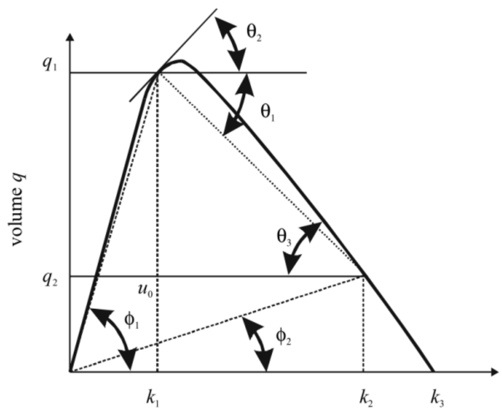

Figure 11: Shockwaves, (Hoogendoorn, 2011)

2.1.7 Capacity

In CIA (Rijkswaterstaat DVS, 2011) the standard situation implies a heavy goods vehicle (HGV) volume that equals 15% of the total volume. Alternative percentiles of HGV can be calculated with the following table.

	to % HGV (with pce factor 2.0)						
From % HGV	0%	5%	10%	15%	20%	25%	30%
0%	1.00	0.95	0.91	0.87	0.83	0.80	0.77
5%	1.05	1.00	0.95	0.91	0.88	0.84	0.81
10%	1.10	1.05	1.00	0.96	0.92	0.88	0.85
15%	1.15	1.10	1.05	1.00	0.96	0.92	0.88
20%	1.20	1.14	1.09	1.04	1.00	0.96	0.92
25%	1.25	1.19	1.14	1.09	1.04	1.00	0.96
30%	1.30	1.24	1.18	1.13	1.08	1.04	1.00

Table 2: Capacity reduction factors for % HGV, (Rijkswaterstaat DVS, 2011)

Note that the pce factor for the HGV is set to 2; this implies that HGV has the same impact as two passenger vehicles. For example an intensity of 1000 veh/h with 10% HGV and a pce of 2 equal 1100 pce/h. (900 vehicles and 100 HGV with a factor 2). The conversion equation is as follows;

$$C_{pae} = C_{veh} * \left[\left(f_{pae} - 1 \right) * \%_{ft} + 1 \right] \tag{2.4}$$

with

C_{pce} = Capacity in pce/h

C_{veh} = Capacity in veh/h

f_{pae} = pce factor for HGV

$\%_{\mathrm{ft}}$ = percentage of HGV (in percentiles, i.e. 10% is 0.10)

The CIA mandates a pce factor of 2.0 for standard situations. To calculate reduction factors for all the percentages of freight transport, the following equation can be used.

$$C_{veh} = \frac{C_{pae}}{\left[\left(\mathrm{f}_{pae} - 1\right) * \%_{\mathrm{ft}} + 1\right]} \quad (2.5)$$

2.1.8 Conclusions

From the theories on traffic flow the most important finding is the relation between: speed, density and intensity. The relation between these macroscopic values is explained with the fundamental diagrams; in this thesis the simplified modelling diagram of Daganzo is used. Furthermore, the literature shows a clear relation between the chosen headway and the capacity of a road segment. During the calibration of the microsimulation model this is a useful relation. From the model of Wu and the theory of the discontinuous diagram, it is derived that during congestion, the queue discharge capacity is lower than the capacity at the start of congestion due to the “capacity drop” and typically is around 10%. The capacity drop is used in order to calibrate the maximum free flow of the microscopic simulation program.

The queuing model in *Figure 10* shows that the maximum queue length is when the oversaturation ends, i.e. the demand becomes lower than the capacity. Furthermore, it shows that the delay increases as the oversaturation duration increases. This fact serves as one as the basic principles for this thesis when evaluation different detection times, i.e. a quicker handling and detection of incidents should decrease the traffic delay.

Shockwaves originate from a sudden and substantial change in the state of the traffic flow. The speed of the shockwaves is defined by the equation; $\omega = \frac{q_i - q_j}{k_i - k_j}$. This equation gives an indication that if $k_i - k_j$ is small, i.e. before the accident the density is already high, the shockwave will propagate itself quicker upstream. This relation is important when modelling different I/C ratios in the model. Note that the maximum speed lies somewhere around 20 km/h.

2.2 Traffic Safety

Besides the effects on the traffic flow, this thesis also tries to give an indication of the safety aspects surrounding incidents. In this chapter an indication will be given of which traffic safety theories are relevant and how these can be analysed from the microsimulation data by using (surrogate) safety indicators. At the end of this chapter the applied safety indicators and their threshold values are chosen.

2.2.1 Safety Indicators

Safety is an ambiguous term; it can refer to: a state of feeling, a level of risk, or a flat number of incidents that have occurred during a certain time span. In the world of traffic, safety is the result of a traffic system influenced by factors such as: driver behaviour, car performance, and external surroundings. (Archer, 2005) describes traffic safety as:

" …. (traffic safety) is implicitly accepted as being related to the negative performance of the traffic system measured by traffic accident frequency and outcome severity. At the individual level, experienced traffic safety is related to the absence of danger and feeling of security"

In this definition there are two parts: firstly the negative performance that is measured by traffic accident frequency combined with their outcome, and the experienced feeling of security of the driver. The latter is a subjective and therefore hard to measure. Therefore the focus is mostly on the first part of the definition, since it is a measurable dimension.

Commonly this is done by "before and after" studies in which a level of safety is observed on a freeway over a time period before and after the implementation of a traffic measure**.** However studies of (Chin & Quek, 1997) have shown it is difficult to give statistically reliable statements about the number of incidents in a fixed location.

Another way to measure traffic safety is looking at situations that have led to near-accidents. These near-accidents were introduced in the form of traffic conflict situations. These situations have a higher occurrence than actual accidents, and that there is a relation between these conflicts and actual accidents. An accepted definition of a traffic conflict situation is given by (Amundsen & Hydén, 1977):

"…an observable situation in which two or more road-users approach each other, in time and space, to such an extent that there is a risk of collision if their movements remain unchanged"

As stated before, conflicts occur with a higher frequency than actual accidents, and therefore a conflict does not always lead to an actual accident. However according to (Gettman & Head, 2003) a higher frequency of traffic conflicts leads to a lower level of traffic safety. This makes the number traffic conflicts a useable indicator of traffic safety.

Although conflicts are not necessary real incidents they can lead to undesirable situations. What makes these conflicts so interesting is that they can be both indirectly observed in practise and in microsimulation models. The next paragraph will discuss how safety indicators can be examined with the help of surrogate indicators.

2.2.2 Surrogate Traffic Safety Indicators

The previous paragraph states that safety can be measured is with "before and after" studies; however, in this thesis this kind of study cannot be conducted as there is no before or after study available. The amount of traffic conflicts however, forms a useable indicator of the traffic safety.

It is not simply possible to query the simulation program to count the amount of traffic conflicts. In order to detect the traffic conflicts, measureable indicators, directly extrapolatable from the microscopic simulation model, are needed. The solution can be found in "Surrogate Traffic Safety Indicators" which can be used to indicate a traffic conflict.

(Gettman & Head, 2003) propose the following surrogate safety indicators:

- Time to collision;
- Post-encroachment time;
- Deceleration rate;
- Encroachment time;
- Gap time;
- Initially attempted post-encroachment time;
- Proportion of stopped distance and
- Headway distribution.

For this thesis the focus will be on Time to Collision and the deceleration rate, as they are of most importance on longitudinal movements which are mostly present on highways accidents.

2.2.3 Time to Collision

Time to collision (TTC) is proposed as the primary surrogate traffic safety indicator. As the name indicates, the TTC-value can only be derived for vehicles on a collision course. Note that the TTC indicator only expresses safety related to the longitudinal driving task and this should be kept in mind when interpreting the indicator (Minderhoud & Bovy, 2001).

The TTC values are calculated by taking the difference in distance and speed of the following and leading vehicle. With the speed and distances the theoretical time it will take for the vehicles to collide is calculated. To calculate the TTC-values the following equation is used:

$$TTC_i = \frac{x_{i-1}(t) - L_{i-1} - x_i(t)}{v_i(t) - v_{i-1}(t)} \qquad (2.6)$$

Where

- x_{i-1} = position car $i-1$
- x_i = position car i
- L_{i-1} = length car $i-1$
- v_{i-1} = speed car $i-1$
- v_i = speed car i

This is visually displayed below in *Figure 12*. Note that for the calculation of the TTC-value the speed differential at t is assumed to remain constant during the hypothetical collision course.

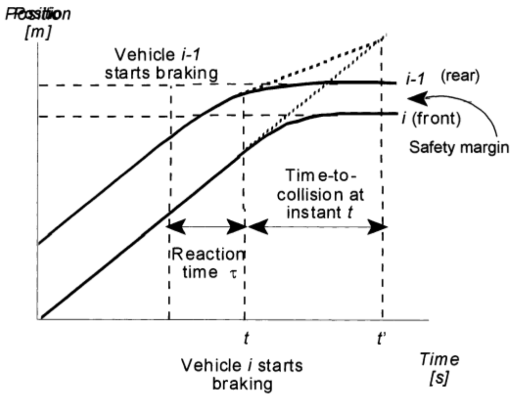

Figure 12: Time to Collision illustrated with vehicle trajectories (Minderhoud & Bovy, 2001)

Because the equation only includes relative speed and does not include absolute speed, researchers have disputed that a lower TTC accurately indicates an increase of the accident severity (Ian Noy, 1997). A lower TTC-value however still directly indicates a higher risk of an accident occurring.

2.2.4 Number of Conflicts

To give a representation of the total amount of times a vehicle has gone below the TTC value the Number of Conflicts indicator is used. A conflict is described by (Amundsen & Hydén, 1977) follows:

"…an observable situation in which two or more vehicles approach each other in time and space and there is a risk of collision if there movements remain unchanged"

In order to compute the number of conflicts occurred (Drolenga & Dijkstra, 2007) use the following equation.

$$NOC_i = \sum_{n=0}^{T} \delta_i(\zeta_n) \qquad (2.7)$$

where:

$$\delta_i = \begin{cases} 0 & \text{else} \\ 1 & \text{if } 0 \le TTC_i(\zeta_n) \le TTC^* \text{ and } TTC_i(\zeta_{n+1}) > TTC^* \end{cases}$$

ζ_0 = point in time when vehicle i enters the network

ζ_T = point in time when vehicle i leaves the network

2.2.5 Time Integrated TTC and Time Exposed TTC

(Minderhoud & Bovy, 2001)have suggested extensions of the TTC indicator: the Time Integrated Time to collision (TIT), and the Time Exposed Time to collision (TET). The TET indicator is a sum of the total time in which the TTC-value is below the set critical value TTC*; the lower the TET-value, the less time a vehicle is in conflict, indicating a higher level of safety. The TET-value can be calculated as follows.

$$TET_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{sc} \qquad (2.8)$$

With

$TET_i^* = TET$ value for vehicle i

$$\delta_i = \begin{cases} 0 & \text{else} \\ 1 & \text{if } 0 \le TTC_i(t) \le TTC^* \end{cases}$$

$\tau_{sc} =$ time interval (s)

A disadvantage of the TET indicator is that it is not affected when the TTC changes below the critical value of TTC*. (Minderhoud & Bovy, 2001) suggest that a lower TTC-value, suggests a lower level of safety. In order to take the TTC-value into account the TIT indicator has been developed (Minderhoud & Bovy, 2001). The TIT indicator includes both the value and the duration of the TTC below the set critical value. The TIT value can be calculated as followed.

$$TIT_i^* = \sum_{t=0}^{T} \left[TTC^* - TTC_i(t) \right] \cdot \tau_{sc} \quad \text{for } 0 \le TTC_i(t) \le TTC^* \qquad (2.9)$$

Both the TET and the TIT indicator are visually explained in Figure 13, the TIT is represented by the black surface in.

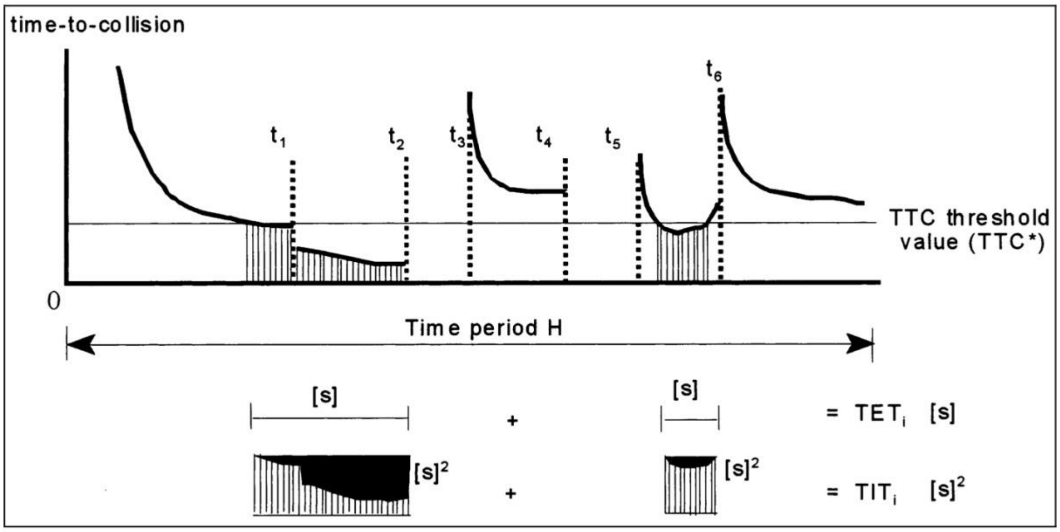

Figure 13: Time Integrated TTC and Time Exposed TTC (Minderhoud & Bovy 2001)

Critical TTC-Value

To calculate the TIT, a TTC-critical value is required, (van der Horst, 1190) suggests that a TTC critical value of 1.5 seconds should be used. (Minderhoud & Bovy, 2001) use values for the TTC-critical of 1.0, 2.0 and 3.0 seconds. (Hirst & Graham, 1997) suggest that a TTC-value of 4.0 seconds should be used; the limit to distinguish between drivers who unintentionally find themselves in a conflict, and those who remain in full control. (Archer, 2005) also uses a critical TTC-Value of 3.5 seconds. Lastly (Ozbay et al., 2008) suggest that when simulating traffic safety indicators one should realise that simulation models are very “cleanly” simulated and the simulated drivers do not suffer from: distraction, misjudgement, and other errors occurring near incident locations. Therefore, a slightly higher critical TTC-value should be used. For this research the value of the critical TTC-value of 4.0 seconds is chosen.

2.2.6 Deceleration Rate

The Deceleration rate measures the highest rate at which vehicles must decelerate in order to avoid a collision. (Hydén, 1987) suggests that the deceleration rate is an important aspect to measure the severity of a conflict. (Hydén, 1987) proposes the following table as a measurement for the severity.

Conflict level	Deceleration-to-Safety	Description
No Conflict	Braking rate <= 0 m/s^2	Evasive action not necessary
No Conflict	Braking rate 0 to -1 m/s^2	Adaptation necessary
1	Braking rate -1 to -2 m/s^2	Reaction necessary
2	Braking rate -2 to -4 m/s^2	Considerable reaction necessary
3	Braking rate -4 to -6 m/s^2	Heavy reaction necessary
4	Braking rate > -6 m/s^2	Emergency reaction necessary

Table 3: Conflict levels per Deceleration rate, (Hydén, 1987)

For this thesis conflict levels 3 and 4 are considered as an unwanted deceleration, i.e. breaking at 4 m/s^2 is taken as a threshold for a conflict.

Although other surrogate indicates that have been proposed by (Gettman & Head, 2003), they will however not be discussed as they are not of significance for the thesis.

2.2.7 Conclusions

When looking at the subject of the thesis and the described surrogate safety indicators the most important indicators for this thesis will be: the TTC related values (TTC, TET, and TIT), Number of Conflicts, the deceleration rates and the longitudinal conflict. The threshold value for the TTC is set at 4.0 seconds and set at -4 m/s^2 for the deceleration rate. Due to the assumption that all accidents occurring on the freeway will be head-tail collisions the post-encroachment time and the other potential conflict energy conflicts are disregarded as they apply more to conflicts occurring on intersections. Due to the choice in indicators the main aspects from vehicles are; speed, distance and acceleration. It will therefore be important to collect these variables from the microsimulation model. Although this thesis will not differentiate between severities of incidents it should be noted that from the potential collisions energy it is directly showed that higher differences in speed lead so a higher severity of incidents and therefore a lower safety. Furthermore it can be argued that every incident is potentially dangerous and that any incident can lead to more dangerous situations.

2.3 Detector Algorithms

When analysing various literature on detection algorithms three different types of detection are found; algorithms using aggregates (van de Ven, 2007), algorithms using moving averages (Rijkswaterstaat, 2000), and speed undershoot detection systems (Martin, 2003). Although the systems can use the same type of detection systems, e.g. inductive loops, their functionality and algorithms differ. This chapter gives an overview of the commonly used methods of detection in the Netherlands.
The first detection method explained are the algorithms using minute aggregates. (van de Ven, 2007) describes the "Blokkadedetector" and its possible alternative the Presikhaaf algorithm as algorithms used in the Netherlands.

Blockade Detector

The Blokkadedetector algorithm is based on the "California" algorithm and works by recognising typical patterns in speed- and intensity aggregates. The algorithm works by checking if consecutive minute aggregates meet the conditions for speed or intensity patterns characteristic for an incident (van de Ven, 2007). The algorithm is usable in situations where there are regular intervals between detection points, according to (Transpute, 2002) it is usable in: Tunnels, Freeways with signalling or monitoring, and hard shoulder running lanes. (Transpute, 2002) distinguishes the characteristics of the algorithm in two: detection in tunnels and detection on corridors.

Blokkadedetector in tunnels	Blokkadedetector on corridors
• Designed to respond quickly • Detection with small intervals, e.g. intervals of 50m • Sampling every 1 to 2 seconds • Response time circa 15 seconds • Almost no false warnings	• Designed to safeguard long stretched of freeway corridors • Detection with price technical interesting intervals, e.g. 500/1000/2000 meters • Sampling every 20/30/60 meters • Response time correspondingly 1/2/4 minutes • For each incident the time, location, and blockings percentage is given

Table 4: Blockade Detector Characteristics

The algorithm uses three checks which are performed in the three consecutive time steps. During the first check, continuously done for each detection point, the algorithm searches for intensity vacuums. An intensity vacuum is displayed in the *Figure 14*. The vacuums are detected by comparing the measured intensity with the expected intensity for that location and time. To determine the expected intensity, the current and previous measurements are used. Because the algorithm looks for changes in intensities, the system does not work properly when the flow is lower than the available capacity of the incident location, i.e. at low flow rates the incident is not detected.
The algorithm uses two thresholds in order to determine its actions. When the measured intensity is much smaller than the expected intensity the system can, with certainty, report an intensity vacuum and reports an incident (van de Ven, 2007). If the ratio between the measured and expected intensity drops below the highest set threshold the system recognises a disturbance in the traffic flow and reports a *possible* incident. When this occurs the second check is performed.

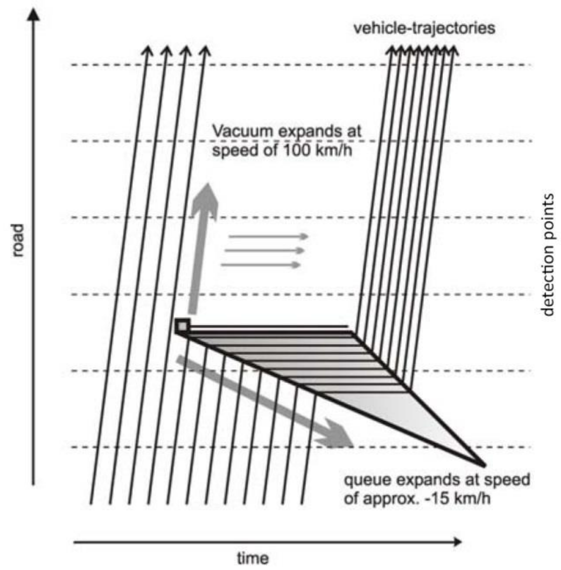

Figure 14: Intensity vacuum, (Transpute, 2002)

The second check is performed on all possible incidents from the first check. During this second check the algorithm checks if the intensity vacuum is still present and if the speed stream downwards is sufficiently high. If an intensity vacuum is present at a detection point downstream during the second check it can be determined an incident has occurred and the system reports this to the traffic controller (van de Ven, 2007).
In check 3 all possible incidents from check 2 are analysed and checked if there is a sufficiently high differences in speed and intensity (van de Ven, 2007). If both conditions are met the system reports an incident.

2.3.1 Presikhaaf

An alternative to the Blokkadedetector is the Presikhaaf algorithm. This algorithm is based on the Blokkadedetector algorithm but predominantly uses the speed differences instead of intensity differences (van de Ven, 2007). Just as the Blokkadedetector algorithm three checks are performed. In order to nullify the naturally present speed variations present the algorithm compares the speed measure in the current interval with the moving average of the previous five intervals. Because a loss in speed can also be the consequence of congestion the system checks if the current speed stream downwards is sufficiently high. To eliminate the chance the speed drop is due to a shockwave, the algorithm checks if the moving average on a detector stream upwards is below a pre-set threshold.
The second check is performed during the next interval and entails the same basic principles of the first step. Additionally the algorithm checks if the intensity stream downwards is lower than the moving average. If all the above conditions are met, the system reports a possible incident and check 3 is performed.
In check 3 the system again checks if the current speed is below the threshold and if the measured speed is lower than the moving average. If all conditions are met an incident is detected and the system gives a warning to the traffic controller.

2.3.2 Automatic Incident Detection

On most Dutch highways there is an Automated Incident Detection (AID) system. This system is part of the Motorway Traffic Management system, which uses detector loops in order to monitor traffic. Although this system was designed in the 70's as a way to detect incidents, it now mostly serves as a system to warn upstream vehicles of an impending congestion. The AID system works by detecting the mean speed of the vehicles per lane and activates when the mean speed drops below a threshold value, currently mostly set at 35 km/h.
The speed is calculated by measuring the time it takes the vehicle to pass over the inductive loop pair, i.e. pass from the first loop to the second loop of the pair. The vehicle speeds are calculated by; dividing the distance between the loops (1 meter) added with loop length (1.5 meters), divided by the travel time. This leads to the following equation (Rijkswaterstaat, 2000).

$$\begin{aligned} v &= (loop\ length + loop\ distance)/travel\ time \\ &= 2.5/travel\ time\ (m/miliseconds) \\ &= 9000/traveltime(km/h) \end{aligned} \quad (2.10)$$

When the mean speed rises above a pre-set threshold, mostly 50 km/h, the system deactivates. In order to diminish the influence of errors the travel times are being filtered for excessive high speeds, i.e. higher than 200 km/h, and low speeds, i.e. lower than 18 km/h. The high speeds are removed whilst the low speeds are increased to 18 km/h. The pre-set thresholds of 35 and 50 km/h are set in order to avoid the system to switch on and off quickly; increasing the credibility of the system (Schelling, 2010). According to the specifics of (Rijkswaterstaat, 2000) the maximum recommended distance between detectors for the MTM system is set at 500 meters.
When the AID system detects congestion it will send a signal to the VMS above the road, warning the upstream vehicles. This is done by displaying [50] on the signals where the congestion is detected and placing speeds of [50] and [70] on the two upstream signals. This is visually displayed in *Figure 15*. These same speed limits are applied when an incident is detected with an incident detection system.

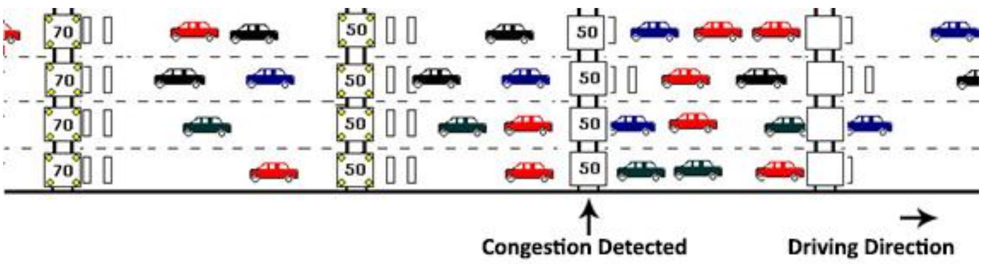

Figure 15: AID system, driving direction towards the right

2.3.3 Speed Undershoot Systems

The above algorithms and the AID system all work by measuring average intensities or speeds over a certain time period or multiple vehicles. In order to detect single vehicles below the threshold "snelheids onderschrijdings systemen", i.e. speed undershoot systems, can be applied. In contrast to the algorithms or the AID system these system give a warning to the traffic controller when a single vehicle is below the speed threshold. To detect the vehicle speeds various systems can be used of which an overview is given in chapter 3. One of the biggest differences between the systems is the differentiation between "zone" and "point" detectors, i.e. can the system detect over a stretched zone or only at a single location. Especially for a point detection system the difference between the detection points determines the speed of detection. For this thesis the focus will be on the comparison of the various speed undershoot systems and their interval distances, throughout the remainder of this thesis the systems will be addressed as the standstill detection systems.

3

Detection Systems

In the previous chapter the required theories on traffic safety, traffic flow, and detector algorithms are discussed. The goal of this chapter is: introducing the detection systems that will be analysed, providing criteria relevant to determining the functionality of the systems, and giving an evaluation of the various systems based on the found criteria.

3.1 Selected Detection Systems

This paragraph introduces the various detection systems that are evaluated throughout the continuation of the research.

3.1.1 Point versus Zone Detection

Before discussing the various detection systems, it is important to make a distinction between the various standstill detection systems. The interviews and literature show that the standstill detection systems can be split up into two main detection methods; point detection and zone detection. A point detection system only detects vehicles directly above or below the detection point. A perfect example is the inductive loop, which can only detect vehicles directly above the loop. Due to this detection method, the system is more likely to detect the congestion occurring due to the incident, rather than detecting the incident itself. The corresponding detection time of the point detectors is therefore related to the distance between the detection points of the system.

Zone detection systems are able to detect vehicles not only above or below the detector, but can detect all vehicles in a stretched detection zone with a single detector point. An example of a zone detection system is a Video Image Processing (VIP) detection system, e.g. a camera detection system. As opposed to the point detection system, zone detection systems can directly detect the incident vehicle and do not rely on the build-up due to the incident. The difference between these two detection methods will serve as one of the main input for the microsimulation model.

3.1.2 Detection Systems

As described in the research boundaries, only on-the-shelf available detection systems currently available in the Netherlands are included. From conducted interviews and found literature, the following detection systems are included:

- Induction loops,
- Infrared systems,
- Radar systems,
- Video Image Processing (VIP) systems,

Within the selected detection systems some variations are present:

- Infrared systems have both passive and active detection systems,
- Radar systems can both be zone and point detection systems,
- Inductive loops can be used for standstill detections systems as well as for the AID system.

Radar

Radar detection systems are both available as point or as zone detection systems. An example of a radar point detection system is the Viafalcon system, currently applied in the Netherlands. An example of a radar zone detection system is the Navtech ClearWay Radar System used in the Hindhead tunnel, A3 in the United Kingdom[1]. For this thesis the Viafalcon will be used as the radar detection system due to its common use in the Netherlands.

Infrared

Infrared detection systems can be divided into passive and active infrared systems. Active infrared systems emit an invisible, low-energy beam and measures the time for the reflected energy to return to the detector; a lower return time indicates the presence of a vehicle. The system measures vehicle speeds by emitting two or more beams and records the times at which the vehicles enters each beam. Active infrared systems can detect: volume, presence, classification and speed. Passive infrared systems detect vehicles by responding to thermal radiation changes; indicating a presence of a vehicle. Passive infrared systems can detect volume, presence, occupancy, and speed within multiple detection zones.

Inductive Loops

Inductive loops detect metallic objects that disrupt its magnetic field, i.e. vehicles. When a vehicle passes over a loop, the loop inductance is reduced and the oscillator frequency is increased; indicating the presence of a vehicle. Inductive loops can detect: volume, classification, occupancy, presence, and speed when placed in pairs.

As described in paragraph 2.3 inductive loops are used for the AID system, but can also be used as standstill detection systems. Although the AID system will be integrated into the microsimulation model, during discussing the referred loops are considered as standstill detection systems.

[1] http://www.navtechradar.com/files/hindhead-tunnel-a3-case-study.pdf, last visited 19-2-14

3.2 System Criteria

Criteria are required to determine the functionality of the various detection systems. This paragraph provides a list of criteria distilled from found literature and conducted interviews. Not all found criteria can be simulated in the microsimulation model. Hence, this chapter also gives an evaluation of the various detection systems based on the criteria that cannot be simulated.

Stakeholders

To determine which parties should be interviewed, it is important to determine the stakeholders for the standstill detection systems. In the eighties' (Edward Freeman & Reed, 1983) proposed a definitions for the term "Stakeholder":

"Any identifiable group or individual on which the organization is dependant for its continued survival"

For this research the definition is rewritten to suit the detection systems. The following definition is used:

"Any identifiable group or individual who can affect or is affected by the selection of the standstill detection systems"

With this new definition the following stakeholders are identified, note that these are in no particular order.

- Road users
- Contractors, installing the systems
- Rijkswaterstaat, the main road owner
- Provinces and other road owners
- Traffic Centres Operators, users of the system
- Emergency services
- Contract writers

Rijkswaterstaat is classified as one of the main stakeholders as it represents the main owner of the Dutch freeways. As the main owner, they are the client which specifies the functional requirements in most of the projects that involve the detection systems. The same rhetoric applies to the Provinces and other road owners, albeit that the number of projects is smaller. Lastly, the traffic centre operators are identified as one of the main stakeholders; they are the direct users of the systems and as a part of Rijkswaterstaat have indirect influence on the set specifications.

Although contractors have an interest in the specifications set by the client, they do not have a significant influence on the set specifications criteria. Road users and emergency services do not have significant power in determining the functional requirements on the detection systems and have a low interest on the functionality of the system.

From the above analysis the following stakeholders have been selected for interviews:

- Rijkswaterstaat
- Traffic Centre Operators
- Province

Because the research is done at the engineering consultancy Witteveen+Bos, which often works in relation with Rijkswaterstaat, additional interviews have been conducted with co-workers at Witteveen+Bos involved with the decision process for standstill detection systems.

Found Criteria

From the interviews various criteria are distilled and displayed in the table below.

Detection Requirements	Criteria	Goals
• Detection of Congestion • Detection of Wrong way drivers • Detection of standstill / slow moving vehicles • Detection of Speed • Detection of other possible blockades	• Accuracy • Detection Time • Costs • Environment impact on accuracy • Other influences on accuracy [(1)] • Flexibility of the system • Installation method and Maintenance • Collection capability for other traffic data	• Prevention Secondary accidents, i.e. improve safety • Prevention of back spill of congestion into tunnels • Accessibility for emergency services • Improving Traffic Flow

Table 5: Detector Criteria

[(1)]Impacts such as location, type of road, and traffic density.

From the table certain aspects such as detection time and the improvement of the traffic flow and safety are tested within the simulation model. However, not all requirements and criteria can be modelled in the simulation program. To give an insight into these remaining requirements and criteria, gathered information from the interviews is used. Because the information derived from the interviews is limited, the gap is supplemented by the literature found on detection systems.

The study of (Martin, 2003) gives an overview of the criteria that should be considered when selection the standstill detection systems, and provides a methodology to select the appropriate system. An adaption of the flow chart is displayed in *Figure 16*. The mentioned criteria include: detection data, suitability for installation location, data accuracy, costs, and ease of installation and maintenance.

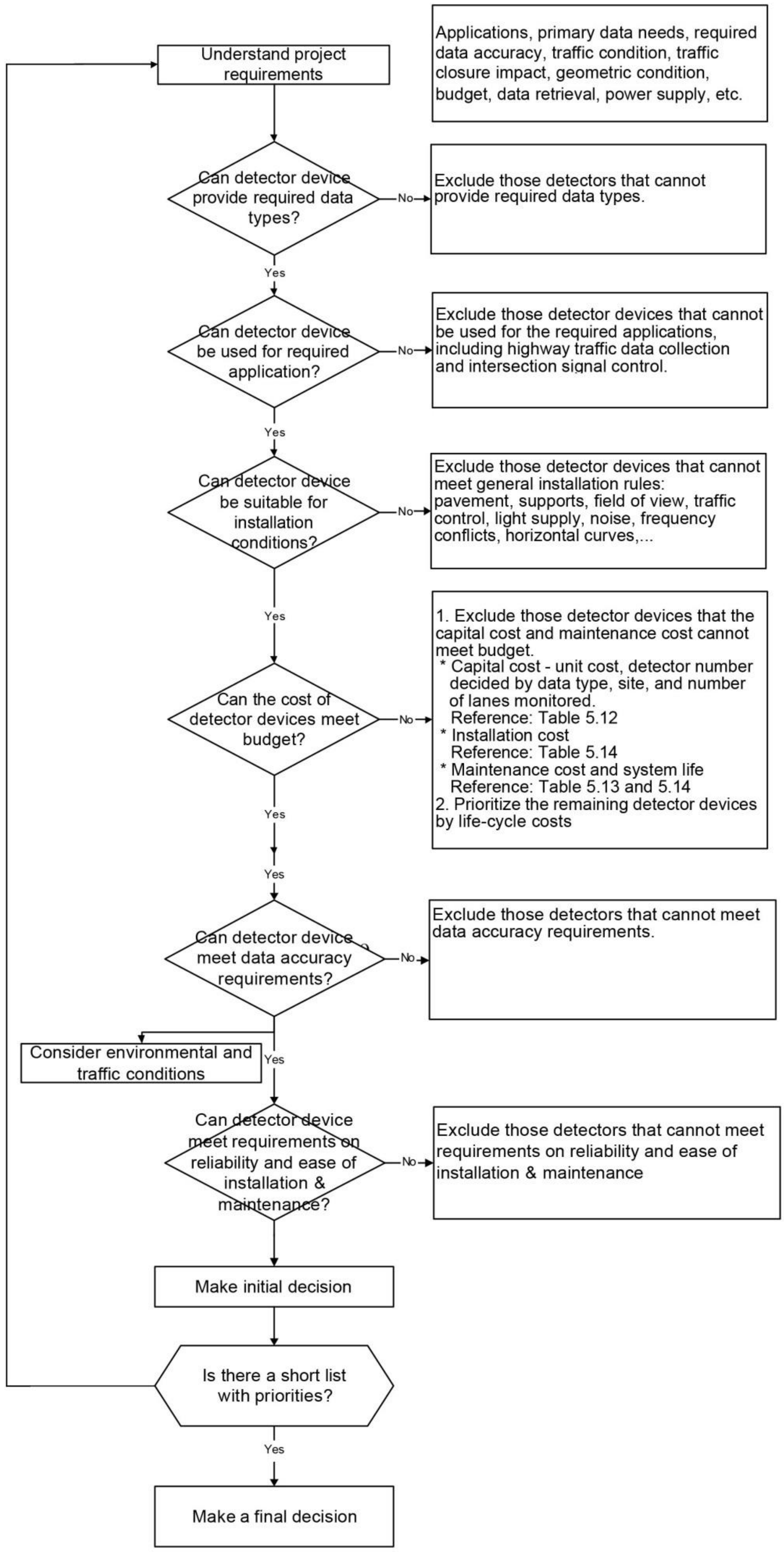

Figure 16: Detector Selection Procedure , (Martin, 2003)

3.2.1 Traffic Data Collection

The first criterion included in the study of (Martin, 2003) is the "Data Collection", i.e. which data each detection systems is capable of gathering. The data collection comprises of: volume, speed, classification, occupancy, and presence (i.e. completely stopped vehicles). The requirements found from the interviews show that the collection of wrong-way drivers and other possible blockades is not included in the list provided by (Martin, 2003). By integrating these two new data collection requirements, the following table is created.

Detector Type	Volume	Speed	Classification	Occupancy	Presence	Wrong way	Other blockades
Inductive Loop	✓	✓	✓	✓	✓	✓[2]	✗
Active Infrared	✓	✓	✓	✗	✗	✓	✗
Passive Infrared	✓	✗[(3)]	✓	✓	✓	✓	✓
Radar	✓	✓	✓	✓	✗	✓	✗[1]
Video	✓	✓	✓	✓	✓	✓	✓

Table 6: Detection data per detection system

[(1)] *Radar detection systems rely on detecting movement, absolute still standing objects are not detected.*

[(2)] *Induction loops are able to detect wrong way drivers, but have an inherent defect, see below.*

[(3)] *Passive infrared systems are only able to detect speed with multiple detection zones*

Induction Loop Wrong-way drivers detection

Inductive loops are able to detect speed and wrong way drivers only when they are placed in pairs; a single loop is only is able to detect volume and presence. Note that although inductive loops can detect wrong way drivers when placed in pairs, they have an inherent defect in detecting them. Wrong way drivers are detected if a vehicle "activates" a downstream inductive loop before "activating" the upstream loop, i.e. the vehicle drives in the wrong direction. However, the loops can give a false warning if a vehicle lane changes on top of the loop; this is explained in Figure 17. The figure shows a vehicle lane changing, from the top lane to the middle lane, activating the loops marked with "1". The next vehicle activates the loops with "2", leading to a false warning for a wrong way driver on the middle lane. Frequent false warnings can lead to a lack of trust in the system with traffic control operators. Note that the second vehicle is not required to switch lanes to create a false warning.

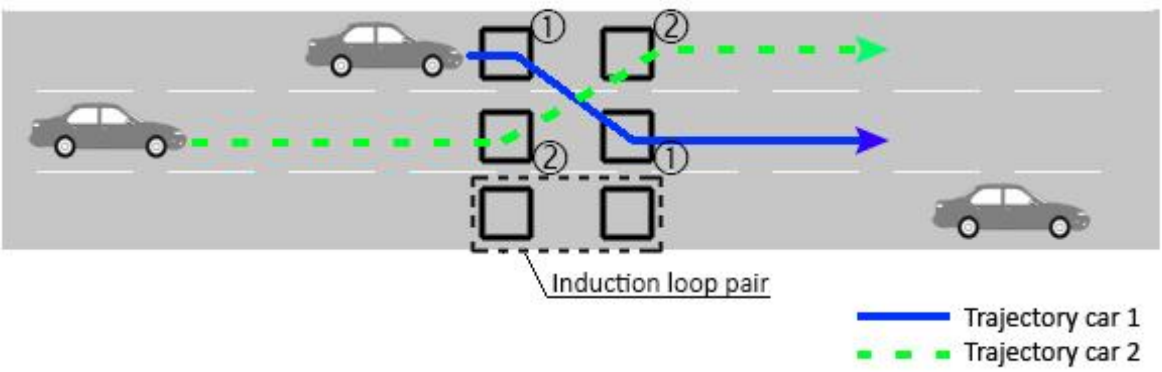

Figure 17: False Wrong way driver detection

Passive Infrared Speed detection

Passive infrared detectors can only detect the speed of individual vehicles using multi-zone detections. Although this enables the system to calculate the average speed, volume, occupancy accurately for the traffic flow, it is unable to calculate individual vehicle speed. For a road with multiple lanes the system is no longer able to distinguish between vehicles, making it unsuited, as a standstill detection system, for road segments with multiple roads.

3.2.2 Data Accuracy

The next criteria suggested by (Martin, 2003) is the data accuracy of the various detection systems. For this thesis the focus is on the environmental and traffic impacts on the accuracy of the systems, i.e. weather conditions and high/low volume. According to (Martin, 2003): wind, precipitation, temperature, shadows, and light can affect the performance of the detector technologies. Furthermore, some systems fail under too high or low traffic volumes.

Environmental impact

From the interviews and literature (Martin, 2003)(Stoelhorst et al., 2011)it became clear that the main issue with VIP is the interference from the environment. Although the VIP detectors are seen as a good detection system, this is seen as its biggest flaw. Below is a summary of the found impacts weather has on VIP performance.

- Clouds, vehicles, or other road side constructions forming shadows on the road leading to false detection of vehicles.
- Heavy rain and snow reduces visibility, and wet road surfaces may become reflective; reducing the performance of the system.
- No visibility during heavy fog, reducing system performance.
- Wind may cause the camera to shake and move.
- In cold weather the exhaust plumes from vehicles may cause false detections.
- Low lighting reduces the performance of the system.

Note that during the interviews Hans van Meurs stated that he has had contact with the University of Dresden; they had promising research in order to solve these issues.
Although the VIP detectors are influenced the most by the environment, other systems are affected as well. From the study of (Martin, 2003) the following effects are found.

Inductive Loop
- High temperatures may cause the asphalt to shift, damaging the inductive loops.
- Snow removal equipment may damage the loops.

Active Infrared
- Affected by heavy rain or snow

Radar
- May be affected if other powerful radars are in the vicinity.

The above found results are summarized in the following table.

Detector Type	Precipitation	Wind	Temperature	Light
Inductive Loop	✗	✗	✓	✗
Infrared	✓[1]	✗	✗	✗
Radar	✗	✗	✗	✗
VIP	✓	✓	✓	✓

✓ = affected
✗ = not affected

Table 7: Aspects affection detector accuracy

[1] *Only active infrared systems are affected by precipitation*

3.2.3 Installation and Maintenance

The effort required for installing and maintaining the various detection systems depends mainly on which category the systems belongs to; intrusive or non-intrusive detection systems. (Bennett, Chen, & Flintsch, 2007) defines Intrusive detectors as: detectors that required placement on top of, or in, the road to detect vehicles. Non-intrusive detectors are defined as systems that do not interfere with traffic flow, either during installation or operation. In this thesis the inductive loops and the radar are considered intrusive detectors; installation and maintenance of both detectors requires lane closure.

Inductive loop

Inductive loops are the least favourable system regarding installation and maintenance. To function, the inductive loops are imbedded into the road. Because inductive loops are embedded into the road surface, they are not suited for steel bridges; steel bridges interfere too much with the inductance of the loops. Furthermore, when the loops are installed incorrectly their performance suffers greatly, an example is the Sijtwendetunnel, in which the steel reinforcements were installed too high, leading to an almost constant signal from the inductive loops (M. Hernandez, 2013, interview). During installation and maintenance the lane is closed for traffic, according to (Martin, 2003) the installation can take up to two days. Finally, the installation of inductive loops is permanent; when lane configurations change, the induction loops may lose their function and are therefore not practical for temporary situations.

Radar

Although the radar detection system is not embedded into the road surface it is deemed an intrusive system; installing the systems above the lane requires a lane closure. As opposed to the inductive loops, radar systems are not embedded into the road surface. When the lane configuration changes, the radar systems can be move accordingly and are therefore suitable for temporary situations.

In order to detect individual vehicle characteristics, the radar systems have to be positioned in an overhead position. When positioned in sidefire position the systems can no longer provide the same level of performance. The overhead position requires a gantry over the road, at VMS locations this will not be a problem as there is a gantry present. However, standstill detection systems require multiple detector points, requiring an overhead installation for each detector point. The consequences for each traffic scenario are elaborated in chapter 6.

Infrared and VIP

Infrared and VIP detectors are non-intrusive detection systems. The systems can be placed on supporting structures adjacent to the road. This means that for these systems the ease of installation is deemed high and maintenance of these systems does not interrupt the traffic flow. VIP detectors do require regular maintenance (cleaning) to keep high quality images. According to (M. Hernandez, 2013, interview) this is done monthly in the winter and bimonthly in the summer. Both the infrared and VIP systems can be adjusted and moved according to the current configuration of the lanes, making these systems more suited for temporary situations.

3.2.4 Costs

Another important criterion of the systems is the price of each of the systems. To give an insight in the costs of the systems, this paragraph discusses the costs based on: number of required detector points, Life-cycle costs, Equivalent Annual Costs (EAC), and the lifespan of the various systems.

Numbers of detectors

One of the main aspects related to the costs of the detection systems is the number of detector points. To determine the number of detectors, it is important to know the detection area of the various systems, i.e. maximum distance and number of lanes. To make a fair comparison of the systems, the detected area is set at 500m for a three-lane highway; equivalent to the distance between two consecutive MTM portals. For point detectors with a spacing of 100m, 5 detection points are required. Because loops are placed in pairs, the number of required loops is 30. An overview of the systems is displayed in *Table 8*.

Detector Type	Lanes	Distance	Number of Detectors
Inductive Loop 25m	Single	Point detection	120
Inductive Loop 50m	Single	Point detection	60
Inductive Loop 100m	Single	Point detection	30
Infrared 25m	Single	Point detection	60
Infrared 50m	Single	Point detection	30
Infrared 100m	Single	Point detection	15
Radar 25m	Single	Point detection	60
Radar 50m	Single	Point detection	30
Radar 100m	Single	Point detection	15
VIP	Multiple (1)	200m (1)	3

Table 8: Number of Detectors per Detection System

(1)Interview with Traficon

Cost per Detector

To calculate the initial costs of the system, the price per unit is needed. This is a tricky subject due to the resistance of suppliers regarding prices for their systems. This is reflected in the found prices in the studies of (Martin, 2003), (Bennett et al., 2007), and (RITA, 2010) which show a large spread in the prices. The following table gives an overview of their reported prices. For some of the systems it was able to receive information directly from the suppliers. However, the supplier found prices are not shown in *Table 9*

	Life Span			Initial Cost			Annual Maintenance Costs		
	Martin	Bennett	RITA	Martin	Bennett	RITA	Martin	Bennett	RITA
Inductive Loop	5-15	5-29(1)	5	\$500-\$1k	\$500-\$1k	\$500-\$1.5k	\$60-\$200	\$125-\$350	\$75-\$125
Active Infrared	5-10	-	-	\$6k-\$7.5k	\$6k-\$7.5k	\$4.7k-\$6k	\$100	\$200	-
Passive Infrared	5-10	-	-	\$700-\$1100	\$700-\$1.4k	\$600-\$1k	\$100	-	-
Radar	5-10	10	10	\$900-\$3500	\$400-\$2.5k	\$8k-\$11k	\$100-\$200	\$100-\$355	\$100-\$500
VIP	10	10	3	\$5k-\$17k	\$4k-\$20k	\$18k-\$24k	\$200-\$400	\$250-\$500	\$200-\$300

Table 9, they will be used in the later calculations.

	Life Span			Initial Cost			Annual Maintenance Costs		
	Martin	Bennett	RITA	Martin	Bennett	RITA	Martin	Bennett	RITA
Inductive Loop	5-15	5-29(1)	5	\$500-\$1k	\$500-\$1k	\$500-\$1.5k	\$60-\$200	\$125-\$350	\$75-\$125

Active Infrared	5-10	-	-	$6k-$7.5k	$6k-$7.5k	$4.7k-$6k	$100	$200	-
Passive Infrared	5-10	-	-	$700-$1100	$700-$1.4k	$600-$1k	$100	-	-
Radar	5-10	10	10	$900-$3500	$400-$2.5k	$8k-$11k	$100-$200	$100-$355	$100-$500
VIP	10	10	3	$5k-$17k	$4k-$20k	$18k-$24k	$200-$400	$250-$500	$200-$300

Table 9: Costs per Detector

(1)In the study of (Bennett et al., 2007) it is noted that it is highly unlikely the maximum lifespan will be reached.

VIP systems are implemented on structures adjacent to the road, e.g. poles. Because the intrusive inductive coils do not require these structures, they should be taken into account for the other systems. According to (RITA, 2010) the cost for such a pole is between $4k and $12 in which the low cost is for a 35 feet pole, and the high cost for a 90 feet pole. The costs include: foundation, pole, and labour. These costs can be negated when considering installation in a tunnel as the tunnel itself acts as the support structure.

Cost Assumptions

For this research it is assumed that the standstill detection systems are placed on a new constructed road and can relay the appropriate information to vehicles on the road through VMS above the road. Because the presence of VMS is assumed, the presence of a substation (in Dutch: “Onderstation”) is also assumed. Hence, for each of the detection systems these can be excluded from the prices. This means that only the costs related to the actual detectors are included. Other costs, such as: overhead costs, training costs, costs to connect the system to the centre, and adaptions to the control centre are assumed equal for all systems.

In the microsimulation model it is assumed that the traffic controller is able to apply traffic mitigations (i.e. speed reduction and lane closure) within one minute after the system issued a warning. Before the traffic controller can apply mitigations, a visual confirmation of the situation is required. This visual confirmation is only possible with CCTV cameras present at the incident locations. It is therefore assumed that for each detection system a CCTV camera is present. Hence, the CCTV camera costs are not included in the comparison of the systems. The presence of the CCTV systems is supported by “Landelijke Tunnel Standaard”, which states CCTV cameras are required in tunnels (Rijkswaterstaat, 2012). Secondly, hard shoulder running lanes are not allowed to open without a traffic operator first visually inspecting the lane for obstruction (Hernandez, personal interview), meaning that these lanes can also be visually inspected in case of an incident. Finally, (Rijkswaterstaat, 2006) suggests placing CCTV cameras at bridges that are controlled remotely.

Life Cycle Costs

To compare the costs of the various systems the life-cycle costs (LCC) will be considered. According to (Rienstra & Groot, 2012) the LCC is used by Rijkswaterstaat to achieve an insight into the whole costs of a project. Rijkswaterstaat uses the LCC to decide on the development of projects. The costs that are included in the LCC are: the initial investment cost, operation cost, and the maintenance cost. In the framework of (RWS, 2012) all costs are visualised for a period of 100 years. For the detector systems this is not a reasonable time period due to the advancement of technology, i.e. current systems will be obsolete in 100 years. In order to give a more useful insight into the relative costs of the system, the Equivalent Annual Cost (EAC) will be used.

Equivalent Annual Cost

The EAC is defined by (Brealey, Myers, & Allen, 2008) as the annual cost of owning an asset, including the initial investment, over the asset's economic lifespan. The EAC not only enables the calculation of the total costs of a detector system, but also enables the comparison of the systems with various lifespans; making it a better comparison tool than the LCC. (Brealey et al., 2008) provide the following equations:

$$EAC = \frac{Present\ Value\ of\ Costs}{Annuity\ factor\ of\ Lifespan} \tag{3.1}$$

And,

$$Present\ Value = \sum_{t=0}^{T_{span}} \frac{C_t}{(1+r)^t} = C_0 + \frac{C_1}{(1+r)} + \frac{C_2}{(1+r)^2} \dots + \frac{C_t}{(1+r)^t} \tag{3.2}$$

$$Annuity\ factor = \frac{1}{r} - \frac{1}{r(1+r)^t} = \frac{(1+r)^t - 1}{r(1+r)^t} \tag{3.3}$$

With

T_{span} = Lifespan of asset
C_t = Costs in year t
r = Discount rate, set at 2.5%, i.e. 0.025 by (Ministerie van Financien, 2011).

With the introduction of the equation from (Drummond, Stoddart, & Torrance, 1988)

$$\frac{C}{1+r} + \frac{C}{(1+r)^2} + \cdots + \frac{C}{(1+r)^t} = C * \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right) \tag{3.4}$$

When assuming the costs C_t stay the same after the initial costs, equation (3.1) can be rewritten to;

$$EAC = \frac{C_0 + C * \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)}{\frac{1}{r} - \frac{1}{r(1+r)^t}} \tag{3.5}$$

By applying the above equation to the various detection systems, it can be assumed that the costs from C_0 are the initial costs of purchasing and installing the detection systems. This means that $C_0 = \text{Initial costs for the system} = \text{Initial Cost} * \text{Quantity}$.

If C_0 is denoted as the initial costs, *C* can be seen as the annual maintenance costs of the systems. This means the final equation that will be used to compare the systems will be as follows

$$\left((Initial\ Costs * Quantity) * \frac{r(1+r)^t}{(1+r)^t - 1}\right) + C_{maintenance} \tag{3.6}$$

With

$C_{maintenance}$ = Annual maintenance costs

Lifespan

Equation (3.6) shows that the lifespan greatly influences the EAC of the various systems. Table 8 shows that the spread of the lifespan is not a factor set in stone, especially the inductive loops show a large range in the expected lifespan. Adaptations to the installation of the inductive loops; loops are no longer placed in the top layer of the road, have increased the expected life span of the detector loops. In this thesis a lifespan of 10 years is taken; however, during a five year period approximately 10-20% of the loops will require replacement.

Overview EAC
For this thesis the prices from the three studies are taken and the following prices are created, note that the prices are in no way precise but rather should be seen as an indication of the price level.

Detector Type	Lifespan	Initial Cost	Annual Maintenance Cost	# of Detectors	EAC
Inductive Loop	10	$850	$80	120	$22.000
				60	$11.000
				30	$5.500
Active Infrared	8	$6000	$175	60	$61.000
				30	$30.500
				15	$15.000
Passive Infrared	8	$1000	200	60	$20.000
				30	$10.000
				15	$5.000
Radar	9	$900	$225	60	$20.000
				30	$10.000
				15	$5.000
VIP	20(1)	$12k(1)	$325	3	$3.300

Table 10: Equivalent Annual Cost per Detection System

(1)On the information regarding the VIP contact has been made with Traficon, the price range was set at €3k-€4k per camera; the high end was chosen to incorporate for the installation. Note that for the thesis the dollar / euro ratio is set at 1.

The table shows that the active infrared systems are by far the most expensive detection systems. When comparing the other systems, the costs of: the Passive infrared, Radar, and the Inductive loops are somewhat on the same level. The VIP detection systems are the cheapest solution; zone detection systems are cheaper in comparison than the point detection systems. Note again that the prices should be seen as an indication and are subject to corrections.

Tunnels
According to Traficon, a VIP supplier, the rule for the detection zone of VIP systems is “20 times the camera installation height”. According to the LTS the minimal headroom in tunnels is set at 4.70 meters; meaning in tunnels the detection zone of VIP systems is around ~100 meters. This means that in tunnels the amount of detectors will increase to five, but there is no longer need for a supportive structure.

3.3 Conclusions

Both (Bennett et al., 2007; Martin, 2003) included a list with pros and cons, this list will be complemented with the found information from interviews and other literature. The list can be seen as a summarisation of the found information.

Detector Type	Pro	Con
Inductive Loop	• Mature, well known technology • Not influenced by weather conditions • Cheap unit cost • Provides all basic parameter: speed, volume, classification, occupancy, presence, and wrong way driver detection	• Intrusive detector, i.e. lane closure during installation and maintenance • Multiple units needed per location, leading to high cost • Short life expectancy • Loops can be damaged by heavy traffic and road repairs • Point Detection • Not applicable on bridges with steel interfering with induction • Possible false wrong way driver detection • Replacement of single loop is intrusive • Cannot accommodate change in lane configurations
Active Infrared	• Detects all parameters • Accurate detection • Non-intrusive detector	• Influenced by Heavy snow and rain • Most expensive solution
Passive Infrared	• Detects Presence • Non-intrusive	• Cannot detect individual vehicle speed in situations with more than one lane.
Radar	• Detects all parameters • Not affected by weather conditions • Less intrusive than inductive loops • Can be moved to accommodate different lane configurations • Cheap unit costs	• Doppler cannot detect stopped vehicles • Affected by other radars in the vicinity • Affected by tunnel walls and noise barriers.
VIP	• Large detection zone (~300m) • Adaptable detection zone • Detects all parameters • Low costs due to large detection zone • Low maintenance • Non-intrusive detector	• Weather conditions influence the performance • Lower height leads to smaller detection zone • May generate false warnings due to lighting conditions creating shadows

It can be concluded that zone detection methods have a lower EAC compared to point detection systems. Although unit prices are higher, the larger detection zone means fewer detectors are needed. The EAC show that VIP systems have the lowest annual costs, but their performance is influenced the most by external environmental effects.

4

Model Setup

The previous chapter introduced the criteria relevant to the functioning of the detection system, and provided insights into the criteria that cannot be simulated in the microsimulation model. This chapter discusses the process of creating the final microsimulation model used to evaluate the two different detection methods; point versus zone detection. Paragraph 4.1 shows the calibration of the model in order to simulate Dutch freeways. Paragraph 4.2 gives an overview of all the traffic processes integrated in the model. Finally, paragraph 4.3 shows the final setup of the completed model and explains the basic functionality of the model. The results of the model will be discussed in chapter 5

4.1 Calibration Microsimulation Model

Chapter 1 describes it is not possible to conduct research on real life incidents; hence, this research uses a microsimulation program to simulate the freeway incidents. Note that a simulation is never exactly the same as the reality, as reality can only be observed with actual real life data. However, due to simplifications and generalisation of traffic behaviour, the simulation model can be used to simulate the reality as closely as possible. This paragraph gives an overview of: which microsimulation model is chosen, which parameters have been adjusted, the calibration process, and the final chosen settings for the specified parameters.

4.1.1 Calibration of Microsimulation Model

Because this thesis evaluates individual vehicle safety, it is necessary to use a microsimulation model which individually simulates the vehicles in the model. Currently there are various models on the market capable of simulating individual vehicles, e.g. AIMSUN, CORSIM, FOSIM and VISSIM.

For this thesis VISSIM is the chosen microsimulation, VISSIM was chosen for several reasons. First, due to the personal lack of prior experience with microsimulation models, it was necessary to receive assistance to master the program. VISSIM was chosen because is a well-known program within Witteveen+Bos; their research on traffic flow mostly is conducted with VISSIM, meaning it was easier to request help if VISSIM was used.
Second, besides the available assistance, VISSIM has the possibility to dynamically change the model through the COM interface. This is important when simulating the traffic conditions near the

incident, and the mitigations activated by the detection systems. The COM interface is discussed in paragraph 4.4.3.

4.1.2 Reference Capacity

To calibrate the model, the parameters are chosen in such a manner that the capacity of the model is equal to the reference capacities cited by the CIA (Rijkswaterstaat DVS, 2011).

To calibrate VISSIM to the data in CIA, various traffic setups are taken from the CIA data. The data for highway capacities are displayed in Table 11. Note that CIA uses a maximum speed of 120 km/h, however the capacities do not alter significantly when applying it to a maximum speed of 100 km/h. (Rijkswaterstaat DVS, 2011)

The given capacity in CIA is the free flow capacity, i.e. the capacity before congestion occurs. When combining this with the theorem of the Discontinuous diagram and the findings of (Cassidy & Bertini, 1999) in paragraph 2.1.2, it follows that the maximum capacity recorded equals the free flow capacity. This serves as the cornerstone of the calibration.

Pce vs. veh/h

Earlier studies of calibration by Witteveen+Bos (van Beinum, 2008) have shown that VISSIM has trouble emulating heavy goods vehicles (HGV). Therefore, for this research only regular personal cars are modelled. This is different from CIA in which a standard 15% HGV is incorporated into the values. Using personal car equivalents (pce) solves this problem. For HGV traffic CIA uses a value of 2.0. When implementing this into equation (2.4), the following pce values are used for the calibration of the model.

Setup	Capacity veh/h	Capacity pce/h (factor 2.0)
1 lane freeway	2100	2415
2 lanes freeway	4200	4830
3 lanes freeway	6300	7245

Table 11: Capacity Data from CIA (speed = 120 km/h)

4.1.3 VISSIM Parameters

Although VISSIM has a pre-set set of parameters to simulate the behaviour of the simulated vehicles, a calibration has to be performed to emulate the behaviour of the Dutch highway users. As stated above, the CIA capacities serve as the reference for this calibration. For this thesis, the main focus is on the lateral and car-following driving behaviour parameters. In order to find the correct parameters for both set of driving behaviour parameters, first the car-following parameters are calibrated and secondly the lateral behaviour is calibrated. This is because both set of parameters influence each other in regards to the capacity.

Car following parameters

For the car following parameters, VISSIM has a number of parameters that can be adjusted; however, according to the VISSIM manual (PTV Vision, 2012) the parameters CC0 (standstill distance) and in particular CC1 (headway time) influence the capacity the most. The safety distance of each vehicle is defined as; $\Delta x = CC0 + CC1 * v$. The headway time CC1 has the biggest influence, this is in accordance with equation (2.2) which states the capacity is directly related to the headway. Hence, for this research the focus will be on these two parameters as our reference of CIA is also based on capacities. Furthermore, the calibration study of (van Beinum, 2008) also uses these two indicators as its main calibration parameters. *Table 12* is included to give an insight into the other longitudinal parameters, note however that for this thesis only CC0 and CC1 will be adjusted.

Influences	Name	Description
	CC0	**Standstill Distance:** The desired distance between stopped cars
Thresholds for DX	CC1	**Headway time:** The time (in seconds), that the driver wants to keep to the leading vehicle. Has the greatest influence on the capacity. Safety distance, $\Delta x = CC0 + CC1 * v$
	CC2	**'Following' variation:** Restricts the longitudinal oscillation or how much more than the safety distance a driver allows before moving closer to the leading vehicle.
	CC3	**Threshold for Entering 'Following':** Defines how far before reaching the safety distance the driver starts to decelerate.
	CC4	**Negative 'Following' Threshold:** Controls the speed differences during the 'Following' state. Smaller values results in more sensitive reactions of drivers, resulting in more tightly coupled vehicles.
Thresholds for DV	CC5	**Positive 'Following' Threshold**: See CC4
	CC6	**Speed dependency of oscillation:** Influences distance on speed oscillation while in following process.
	CC7	**Oscillation acceleration** Actual acceleration during the oscillation process
Acceleration Rates	CC8	**Standstill acceleration:** Desired acceleration when starting from standstill
	CC9	**Acceleration at 80 km/h:** Desired acceleration at 80 km/h.

Table 12: VISSIM Parameters

2-to-1 lane Calibration Model

To calibrate the two longitudinal parameters, a 2-to-1 lane model was created with the following ground rules:

- CC1 is the leading variable, only this 'knob' will be altered per calibration run
- CC1 will be calibrated to an accuracy of 0.1
- Only after finding the acceptable value of CC1, CC0 will be adjust in order to further fine-tune the results
- Input flow has to be set on exact numbers, because we do not want a stream in which the demand fluctuates, leading to more scattered results of the calibration. For the final simulation in which we test our detection systems a stochastic input flow is preferred however.
- To nullify the influence lane change parameters have on the model uses two 1-lane traffic flows that merge into one. The cars however are allowed to 'collide' with each other during the merging phase, but as soon as they arrived on the designation lane, regard their safety distance. This leads to a situation where the headway on the final 1-lane directly decides

the capacity as the cars from the arrival lanes also use the safety distance in order to see if they can access the designation lane.

These ground rules lead to the following model displayed in Figure 18.

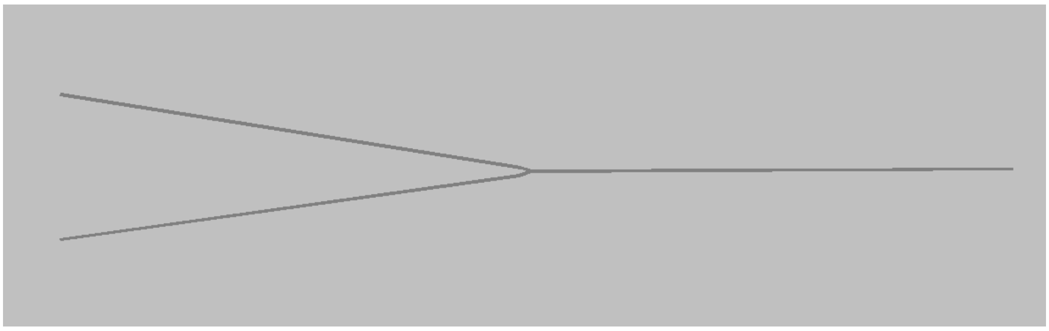

Figure 18: 2-to-1 Lane Configuration Model VISSIM

The choice of a 2-to-1 lane configuration means that the car-following parameters are not influenced by the lane changing parameters, as overtaking is impossible in this model.

Input

For the input, a warm-up period of 5 minutes is taken, from which thereon increments of 25 vehicles per hour are added per minute, see Table 13. This is done for each of the input lanes, resulting in an intensity equal to double the below values on the final lane.

Time (s)	0 -300	300-360	360 – 420	.....	2880 – 2940	2940 - 3000
Input (veh/h)	600	625	650	.....	1675	1700

Table 13: Input for 2-to-1 lane calibration model

Output

For the output of the model, a detector is placed at the end of the link to measure the outflow of vehicles (in pce/h) of the model. This output serves as the output data that used to calibrate the model.

Process

The process of calibrating the car-following parameters is an iterative process in which the parameter CC1 is tested for the range of CC1=0.9 to CC1=1.5. The maximum outflow is calculated for each random seed run, with a 1-minute aggregate. The median result of the runs is seen as the outcome of the particular parameter setting.

Results

The results from the calibration runs are displayed in Table 14.

Variable		Results	Goal	Difference	%	std.
CC1	1.5	1980	2415	-435	-18%	37
CC1	1.4	2100	2415	-315	-13%	59
CC1	1.3	2220	2415	-195	-8%	56
CC1	1.2	2340	2415	-75	-3%	77
CC1	1.1	2460	2415	45	2%	87
CC1	1	2520	2415	105	4%	118
CC1	0.9	2730	2415	315	13%	211

Table 14: Calibration results

The table shows that the results, with the value CC1 = 1.1, gives the best results.

Next, the parameter CC0 is tested, to identify if it has any influence on the results. This is done to exclude the possibility that multiple parameter pairs yield the same result.

For CC1 = 1.1 the following results are produced. By altering the values of CC0 an influence can be found, but the capacity is not significantly influenced by CC0. Thus, the basic value of CC0 = 1.5 is already an excellent value set by VISSIM itself.

Variable		Results	Goal	Difference	%	std.
CC0	1.5	2460	2415	45	2%	87
CC0	1.4	2460	2415	45	2%	88
CC0	1.3	2460	2415	45	2%	91
CC0	1.2	2460	2415	45	2%	90

Table 15: Calibration results CC1=1.1

Finally, the theory that the lane changing parameters do not influence the outcome of the above calibration process, is tested. This is done by altering the lane changing parameters to unrealistic values. The results show that the fluctuation of the lane changing parameters has no effects on the outcome, thereby indicating the model correctly negates the effects of the lane changing parameters.

Consequences for the model

From the results of the calibration of car-following, the following settings for CC0 and CC1 are found:

- CC0 = 1.5
- CC1 = 1.1

These new found parameter settings serve as the input for the second part of the calibration; the lane change parameters.

Lane Change Parameters

For the lane changing parameters, the main parameter adjusted is the *safety reduction factor.* The safety reduction factor influences the safety distance during lane changes. The new safety distance is calculated as follows; *original safety distance x reduction factor.* After the lane change is complete, the original safety distance is regarded again. This parameter is chosen as it directly influences the headway distribution during lane changes and therefore, the capacity. Lastly, the parameter of the Min headway to slower lanes is adjusted. The Min headway defines the minimum distance to the vehicle in front that must be available for a lane change in standstill conditions.

Weaving Model

To calibrate the lane changing parameters in VISSIM, a reference capacity is chosen in CIA (Rijkswaterstaat DVS, 2011) that includes a lot of lane changing. For this research, the reference capacities are chosen from a 2+2 weaving section with a weaving area of 750m, in which the amount of weaving traffic is set to 25, 50 and 75 per cent, see Figure 19.

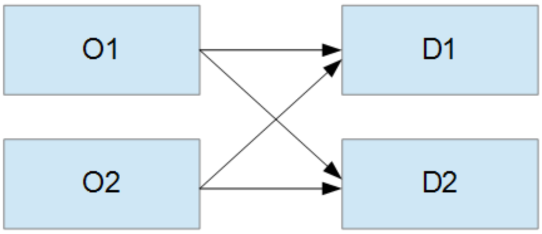

Figure 19: Weaving traffic

In CIA the following reference capacities are found for above origin - destinations.

Setup	O2->D1 [%]	O1->D2 [%]	Capacity [veh/h]	Capacity (factor 2.0) [pce/h]
2+2 Weaving	25	25	7690	8844
	50	50	6640	7636
	75	75	5620	6463

Table 16: Reference Capacities, (Rijkswaterstaat DVS, 2011)

Input, Output and Process

As with the calibration of the car-following parameters, a steady increase is selected for the input for the model. The input is ranged from 50% to 110% of the target capacity, this is in accordance with the calibration report of (van Beinum, 2008). For the output, the outflow of both lanes is taken after the weaving section. Next, the outflow of each lane is added onto each other to calculate the total outflow capacity. The model can be seen in Figure 20.

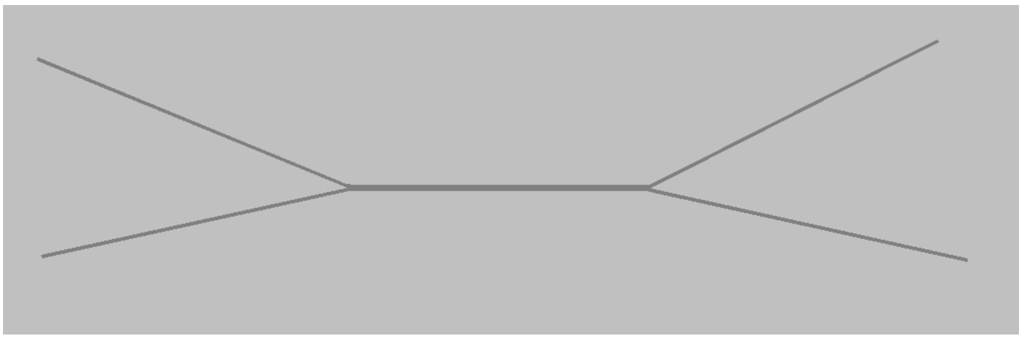

Figure 20: 2+2 Weaving Section VISSIM Model

Results

The results for each of the three weaving levels has been integrated into the below table. This table displays the absolute percentage of difference for each of the reduction factors. To determine which reduction factor suits our reference values, the best two methods have been used. The first method is simply looking at the average absolute difference with the reference values. From Table 17 it shows that the reduction factor of 0.35 has the lowest mean absolute difference. The second method is assigning weights to the results, in which the 25, 50 and 75% weaving results get a weight of 1.2 or 3 according to their level of weaving. Again here the reduction factor of 0.35 gives the best results.

		Percentage weaving traffic			Mean abs	Weighed abs.
		25	50	75	difference	Average
red factor	**0.6**	-5.0%	-5.1%	-5.4%	5.17%	5.23%
red factor	**0.5**	-3.4%	-2.1%	-4.0%	3.16%	3.27%
red factor	**0.4**	-2.9%	-0.1%	-2.3%	1.79%	1.70%
red factor	**0.35**	-2.6%	0.7%	-1.9%	1.75%	1.62%
red factor	**0.3**	-2.2%	3.2%	-2.2%	2.55%	2.53%
red factor	**0.25**	-2.3%	3.6%	0.1%	2.01%	1.64%
red factor	**0.2**	-1.8%	4.8%	0.3%	2.28%	2.03%
red factor	**0.1**	-1.9%	5.0%	3.0%	3.31%	3.50%
red factor	**0.05**	-1.5%	4.8%	2.0%	2.78%	2.87%

Table 17: Results Calibration Model 2+2 Weaving Section

For the above results, the Min Headway during lane change is set to 1.0 meters. As with the process of the car-following parameters, in which after finding the main parameter a second parameter is calibrated, the Min Headway was adjusted to 0.5 and 2.0 meters. However, the results do not significantly alter during these variations. Therefore the Min Headway is kept at 1.0 meters.

Consequences for the model

From the results of the calibration of lane changing parameters, the following settings for the reduction factor and Min Headway are selected.

- Reduction factor = 0.35
- Min Headway = 1.0

These parameters, together with the parameters found for the car-following parameters serve as the main calibrated parameters of the used model.

4.1.4 Conclusions

After the completion of the calibration, the following three parameters are adjusted to simulate the Dutch highway users as closely as possible. For the other parameters, the standard VISSIM parameters were chosen from the Driving Behaviour set "Freeway". Furthermore the Cooperative lane change was selected.

Parameter	Car following CC1	Lane Changing Min. headway	Safety distance reduction factor
Original	0.9	0.5	0.6
Calibrated	1.1	1.0	0.35

Table 18: Adjusted Parameters VISSIM

4.2 Traffic Processes for the Model

Simulating traffic incidents is a very complex process, only calibrating the VISSIM parameters does not include the effects and processes occurring at incident locations. To simulate real life situations more closely, various theories and other effects are implemented into the model. This paragraph serves as an overview for the following theories, processes and other considerations that will be designed into the model:

- Driver compliance to dynamic speed limits
- Incident Management duration times
- Effects of Accidents on Microscopic Traffic Behaviour

4.2.1 Compliance to Dynamic Speed Limit

In paragraph 2.3.2 is it detailed how the activation of the AID system introduces new speed limits to the vehicles through the VMS. When simulating this in the microsimulation, it is important to understand that drivers do not fully comply with the dynamic speed limit.

From the report of (Stoelhorst et al, 2011), which researched the effects of dynamic speed control (Dynamax), it is found that under rainy conditions and implementation of dynamic speed limits, the average speed dropped with 12 to 21 km/h. The speed decrease, without implementation of dynamic speed limits, is around 3 to 8 km/h with rainy conditions. An overview is shown in Table 19: indicating drivers do not fully comply with the displayed maximum speed limit.

Initial speed	**Variable speed limit**	**Average decrease speed**	**Average extra speed decrease**	**Average Decrease / limit**
120 km/h	100 km/h	12 km/h	4-8 km/h	6/20 = 0.3
120 km/h	80 km/h	21 km/h	12-18 km/h	15/40 = 0.38
			Average	0.34 km/h per km/h

Table 19: Speed Reductions under Rainy Conditions

If the values from Table 19 are extrapolated to the speeds of 70 and 50 km/h, from an initial speed of 100 km/h, Table 20 can be created. Note that the results from Table 8 are speed limits applied to long stretches of freeway, and are not introduced with the flashers that are present with the AID system.

Initial speed limit	Variable speed limit	Average decrease speed	Actual decreased speed
100 km/h	70 km/h	30*.34=10	90 km/h
100 km/h	50 km/h	50*.34=17	83 km/h

Table 20: Extrapolation of speed reductions

The study from (Hanckman, 1998) analyses MARE-data, it shows that with a signal displaying [70] km/h the average speed reduced to approximately 90 km/h. Directly after showing [50] there is not a significant speed decrease that can directly be related to the speed limit. Eventually the speed decreases below 50 km/h, this is most probably due to the traffic situation that "demands" slower speeds.

Consequences for the model

When comparing the two studies it seems that the initial reduction from 100 to 90 km/h seems be to be a realistic assumption. For this thesis the simulated speed limits of [70] and [50] are put on 90 km/h in VISSIM.

4.2.2 Incident Duration Times

To simulate the handling of an incident in the microsimulation model, a basic 'template' surrounding the events of an incident is required. In order to create this template, the basic phases from Incident Management (Rijkswaterstaat DVS, 2013) are taken. The 5 basic phases are briefly explained below and displayed in Figure 21.

Detection phase, the incident gets detected through detection systems or the incident is reported

Handling phase, phase between detection and dispatching the appropriate services. This consists of the assumption time (intake, classification), alarming time (deriving which services are needed and alarming them) and the dispatch time (readying vehicle, gear and people)

Response phase, time between dispatching the services and arrival at the incident

Service phase, time duration of the handling of the incident.

Normalization, phase in which the traffic flow returns to normal.

Figure 21: Phases of Incident Management

When simulating these different phase it is importance the duration of each of the phases is known. In the report of (Rijkswaterstaat DVS, 2013) the different durations are given. A distinction is made between the types of incidents that can occur, each having different phase durations.

The different incident categories are:

Category 1

- Broken down car

Category 2

- Broken down lorry
- Incident involving car sustaining only material damage

Category 3

- Incident involving car with injuries sustained to the driver
- Incident involving lorry sustaining only material damage
- Incident involving lorry with injuries sustained to the driver

According to the report of (Drolenga, 2012) the biggest part of the incidents, around 70%, consist of category 1 incidents. For the different incident categories the report gives the different phase times collected by Rijkswaterstaat for the years 2009 - 2012 of which the last 2 years are used for this thesis. The times given here are used in the template modelled in the microsimulation program; the values are visible in Table 21.

2011				
	Handling time	**Travel time**	**Work time**	**Incident duration**
category 1	2	6	22	29
category 2	2	12	40	53
category 3	2	12	53	67

2012				
	Handling time	**Travel time**	**Work time**	**Incident duration**
category 1	1	6	18	25
category 2	1	11	41	53
category 3	2	12	50	64

Table 21: Incident duration Incident Management, (Drolenga, 2012)

Consequences for the Model

With the durations of the different phases of the incident management, the model can be coded to emulate the correct durations. Below is a description of what the different phases mean for the model.

Detection Time

The report does not include the detection time, i.e. the time between occurrence of the incident and the knowledge that an incident has occurred. In this thesis the detection time is calculated with the microsimulation model. For the detection time in the model a maximum detection time of 5 minutes is implemented, it is assumed the incident vehicle has called the emergency services within this time span.

Handling Time

The handling time represents the time between detection of the incident and the implementation of the traffic measures, i.e. lane closures. For our model this time is set on 60 seconds, i.e. 60 seconds after detecting the incident, the corresponding lane will be closed for traffic and/or adjusted speeds are displayed on the VMS.

Handling, Travel and Work time

The handling, travel and work time are added to each other, forming the total dwell time of the incident after detection. The total time of detection, added with the dwell time is referred to as the “standstill period”. Because VISSIM does not allow the alteration of dwell times after a car is parked, the parked vehicle (i.e. the incident) is simply removed from the network after the standstill period has been reached. For the model this means 25 minutes, i.e. 1500 seconds after the incident is detected, the incident vehicle is removed from the model.

Removal of Traffic Measurements

After the removal of the incident, the traffic measurements in the form of the lane closure will be removed. The measurements of the AID system however will still be active and are only removed if the moving average of the measured speeds becomes greater than 50 km/h.

4.2.3 Effects of Incidents on Microscopic Traffic Behaviour

As this thesis focuses on incidents, it is important to obtain a basic grasp of the influence an accident has on behaviour of individual road users. The found information can then be used as an input for our simulation program. Although little research is available on this subject, the dissertation of (Knoop, 2009) has shown that accidents have a substantial influence on the driving behaviour of the road users. The theory states that the attention spent on the accident, leeches from the available attention for the driving tasks, and an increased risk of an accident involving the drivers themselves. This leads to an increased reaction time and higher preferred headway by the driver, which can be achieved by lowering speed or changing lane.

Headway

The results from the analysed data by Knoop are displayed in Table 22. In these results Apeldoorn westbound is the opposite traffic and Gorinchem westbound is in the same direction as the accident. They show that the median headway increased up to 3.2 seconds from a normal median of 1.9 seconds for the lanes in the opposite direction, and an increase to 3.7 seconds from 2.0 seconds for the driving lanes on the same direction. For the traffic in the same direction this means an increase of headway by a factor of 1.85.

	Apeldoorn westbound	Apeldoorn westbound	Gorinchem westbound
Lane	Right	Left	Left
Median headway	3.2 s	2.1 s	3.7 s
Standard dev.	2.7 s	0.9 s	2.4 s
Normal	1.9 s	1.9 s	2.0 s

Table 22: Headway increase due to incident, (Knoop, 2009)

Average speed

As stated a higher headway can be achieved by changing lane or by lowering speed. Knoop has also investigated this and found that the speeds decreased to a minimum at approximately 100m before the incident after which the vehicles start accelerating again. Knoop suggests that this point appears to be the point providing the best view of the incident location.

Queue Discharge Rate at Incidents

The final theorem that is applied from the dissertation of Knoop is the discharge rate at incident locations. Knoop findings suggest that at incident locations the discharge rate is lowered by a factor F. For our model in which 1 out of 3 lanes will be blocked this suggests a capacity reduction factor of 0.54 on the remaining lanes, see table. This drop can directly be related to the increase in headway as 1/1.85 = 0.54.

Lanes blocked	Shoulder	1 out of 3	2 out of 3	0 (Rubbernecking)
Capacity Factor F				
Mean	0.72	0.36	0.18	0.69
Standard dev.	0.09	0.14	0.12	0.08
Efficiency of Lane in Use	0.72	0.54	0.54	0.69

Table 23: Capacity Reduction Factors, (Knoop, 2009)

Consequences for the model

As the main calibrated parameter for car-following behaviour is also based on headway, this theorem can be used in order to adjust the parameters surrounding the incidents. When combining the headway and average speed drop, it can be suggested that at 100m before the incident the headway should be increased by a factor 1.85, leading to a headway surrounding the incident location of 1.1 * 1.85 = 2.0 seconds.

4.2.4 Number of Runs

An important consideration for this thesis is the number of runs that will be run. Therefore it is important to know the required amount of runs in order to ensure statically reliable results. VISSIM uses random seeds that generate traffic and assigns random (within the assigned boundaries) parameters to each vehicle. In order to ensure that extreme random seeds are "filtered" out, multiple runs are required. From these multiple, random seed, runs the median will be used as the results of the total amount of runs.

For one of the scenarios that will be tested in this thesis initially 50 runs were done. From these initial 50 runs the indicators of traffic flow and safety were investigated with the help of a student T-test in order to determine the minimal amount of runs required to ensure statically reliable results. To determine amount of runs, the following equation was used which was derived from (Hale, 1997)

$$N = n_1 \left(\frac{h_1}{\varepsilon * \bar{X}(n_1)} \right)^2 \tag{4.1}$$

Where

N = amount of required runs
n_1 = number of initial runs
ε = confidence factor
$\bar{X}(n_1)$ = mean of initial runs
h_1 = variation of initial run

Where the variation h_1 is determined by:

$$h_1 = t_{n_1 - 1}\sqrt{\sigma^2 / n_1} \tag{4.2}$$

where

$t_{n_1-1;\alpha}$ = t-value for confidence level α
σ^2 = variance of initial run

For the initially tested scenario it was found that with a confidence interval of 5% below or above the mean can be achieved, when looking at the total TIT per run and the growth speed of the congestion, with 95% statistically correctness with 17 runs or less. For this thesis we will round this out to 20 runs per scenario.

4.2.5 Conclusions

From the above theories it shows that when simulating an incident on a highway there are various aspects that have to be taken into account. Simply creating an incident on a highway and seeing how the traffic reacts does not suffice in order to emulate reality. For the model the following conclusions can be taken of which aspects have to be included;

- The AID system uses the bottom threshold of 35 km/h and an upper threshold of 50 km/h.
- The speeds are calculated with a moving average of the last 3 passed vehicles
- When confronted with dynamic speed limits of [70], drivers will slow down from 100 km/h to 90 km/h.
- When confronted with dynamic speed limits of [50], drivers will not show significant decrease unless downstream traffic forces them to slow down.
- The time between detection of an incident and the application of traffic measures on the VMS take 60 seconds.
- 70% of incidents are category 1 incidents with an average incident duration of 25 minutes, i.e. 1500 seconds
- When an incident is visible drivers choose to increase their headway with a factor 1.85.
- Vehicles have the lowest speed approximately 100 meters before the incident, this point seems to be the point with the best view of the incident
- When 1 out of 3 lanes is blocked by an incident, the two lanes still in use have their efficiency reduced by a factor F of 0.54. This decrease in efficiency can be linked to the increase in headway.
- A confidence interval of 5% below or above the mean can be achieved in 95% of the runs with 17 runs or less. For this thesis 20 runs will be used.

4.3 Setup of the Model

Now that the parameters have been calibrated and the considerations for the model are known, the model itself can be created. This chapter will serve as a quick guide into the purpose, basic functionality and setup of the model.

4.3.1 Point versus Zone Detection

The goal of this research is to give an insight into the functionality of the various detection systems and their methods of detection in traffic situations lacking a hard shoulder. Due to the nature of the model it is not possible to simulate all the inherent characteristics of the various detection systems. However, it is possible to simulate the difference between a point detection system and a zone detection system. The characteristics that cannot be analysed in the microsimulation model are discussed in chapter 3

Purpose of the Model

In paragraph 3.2 requirements on the detection are discussed. With the model is only possible to analyse the effects on traffic flow and safety, furthermore we can determine the detection times of the point detector systems per I/C ratio.

To analyse the various detection systems, their functionality is tested according to the effects the method of detection has on the traffic. These effects will be measured in regards to their detection time of the incident and the inherent effects on various aspects of traffic flow and safety. The indicators for these are;

- Traffic flow
  - Delay Time, total delay of the vehicles during a simulation
  - Queue Length, the maximum queue length during a simulation
  - Queue Growth Speed, the time it takes for the formed queue to reach 100.200.300.400.500 and 1000 meters
  - Discharge Rates, the available discharges surrounding incident during the duration of the incident.

- Traffic Safety
  - Time to Collision of individual vehicles
  - Deceleration Rate of individual vehicles

- Detection Time, time it takes the system to detect the incident after it has occurred.

To get these results output files from the various VISSIM runs will be taken and analysed using MATLAB scripts.

4.3.2 Model Design

To obtain the desired output of VISSIM, a model will have to be designed. Because this research wants to be able to give global recommendations, and not solely on one particular road, the model was designed as a simple, 3-lane stretched road. In the following section the setup of the model is quickly explained. Note that in this paragraph only the static components will be detailed. The COM interface, which dynamically controls the model, is explained in the next paragraph.

Network size

Due to limitations of the program not allowing networks greater that 10x10 km, the length of the road is set at 10 km. The maximum size is taken in order to contain the total congestion queue length due to the incident.

Desired Speed

The desired speed of the vehicles is set at 100 km/h because the model simulates a 3-lane freeway with hard shoulder running, on Dutch highways there is a speed limit of 100 km/h on these highways. Furthermore, in tunnels the most common maximum speed limit is also 100 km/h. For the desired speed distribution the standard VISSIM values of a desired speed of 100 km/h are taken.

Driving Behaviour Parameters

After the completion of the calibration, see paragraph 4.1, the following three parameters are adjusted to simulate the Dutch highway users. For the other parameters the standard VISSIM parameters are chosen from the Driving Behaviour set “Freeway”. Furthermore the Cooperative lane change was selected.

	Car following CC1	Lane Changing Min. headway	Safety distance reduction factor
Original	0.9	0.5	0.6
Calibrated	1.1	1.0	0.35

Table 24: Adjusted Parameters VISSIM

Traffic volume

The theory of shockwaves, found in paragraph 2.1.6, shows that the shockwave speed is dependent on the flow. Different flow rates lead to different queue growth speeds; therefore in this research three different flow rates for the traffic volume input are taken. Initially the I/C Ratios of 0.3; 0.6 and 0.9 were chosen, initial runs showed that at the lowest I/C ratios there was no detection able within the pre-set 5 minute threshold. Therefore it was decided to increase the flow.

When combining the Flow / Capacity values of CIA with the capacity of a 3-lane road of 6300 vehicles per hour, the following traffic flow input is set in VISSIM.

I/C Ratio	0.7	0.8	0.9
Volume	4410 [veh/h]	5040 [veh/h]	5670 [veh/h]
Volume, pce	5021 [pce/h]	5796 [pce/h]	6521 [pce/h]

Table 25: Traffic Flow Input VISSIM

In contrast with the calibration of the model, the input for the simulations testing the various detection systems will use a stochastic input for the vehicles. This is due to the fact traffic vehicles never come in a steady and continuous stream.

Simulation and Vehicle Input Duration

Initially the simulation time of the model was set at 1.5 hours, i.e. 5400 seconds. However, it showed that this duration led to congestion growing out of the model. Due to the limitations of the licence, enlarging the model was not an option. Lowering the simulation duration was also not an option, as the congestion does not completely dissolve during a lower period of time. Hence, the decision was made to lower the duration of the vehicle input. After analysing the results it shows that with vehicle input duration of 3000 seconds, each simulation attained their maximum queue length and the congestion did not grow out of the model.

Links

For the links, standard VISSIM settings have been used regarding size and type. However, the theory from Knoop in paragraph 4.2.3 suggests that vehicles choose an increased headway surrounding incidents. To simulate this, the last 100 meters in front of the incident are a different link type. By changing the link type it becomes possible to increase the headway on this link during the duration of the incident. How this mechanism works will be detailed in paragraph 4.4.3. The increase headway choice is visualised in *Figure 22*. The red dotted zone is the increased headway zone and the red vehicle depicts the incident location, located at "x" meters from the first upstream VMS.

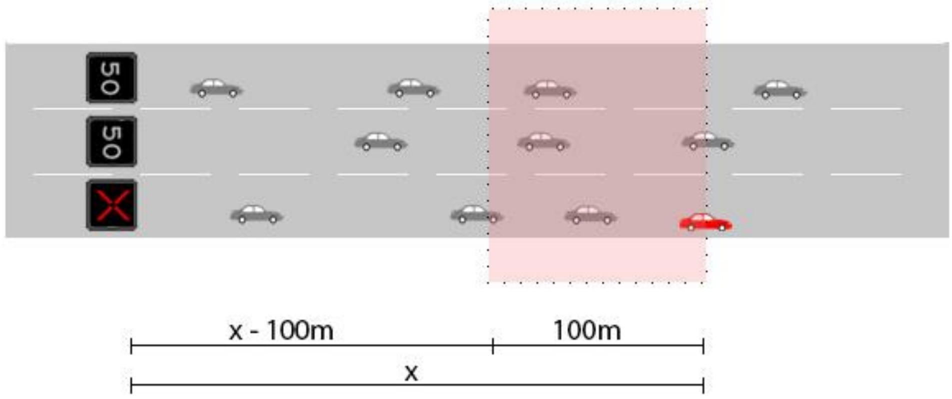

Figure 22: Increased headway zone, x=100.300 or 500m

Incident location

The objective of this research is evaluating the functionality of the various detection systems. When comparing the various systems it is important to have a null-variant to which the results can be compared. As stated above the assumption is made that there is a MTM system in place with an AID system. Unlike standstill detection systems, the AID system is not as effective in detection single stationary vehicles; however, it able to detect the congestions that occur due to the incidents. The time it takes the AID system to detect the congestion is highly dependent on the location of the incident regarding the first AID detectors. To incorporate this, the incident location will be varied to a distance of 100, 300 and 500 meters from the AID system. Furthermore it may be possible that traffic responds differently per incident location.

VMS: Detectors and Speed Decisions

For this research the assumption is made that the hypothetical simulated has a MTM system in place with a VMS. For the model, the MTM system has VMS placed every 500 meters and has the possibility to adjust the maximum speeds of the passing vehicles. In the model this is simulated by placing detectors every 500 meters in combination with speed decisions. The detectors serve as the input for the COM interface, which in turn will control the speed decisions.

Queue Counters

To detect the congestion growth, queue counters have been placed at an interval of 250m across the entire length of the model. The total length of the queue is calculated by adding up the values of consecutive queue counters.

Time section

The delay of each individual vehicle, enabling the calculation of the total delay of each simulation run, is measured over a stretch of 9500 meters.

4.4 Incident Simulation and Detection Methods

After completion of the model setup, the model and incident can be simulated. This paragraph details the method used to simulate the actual incident. Furthermore, the implementation of the different detection methods, point versus zone detection, is explained.

4.4.1 Incident Simulation

Although VISSIM does not give the direct option to simulate an incident, it is possible to simulate the effect by various methods. The method used in this research is the usage of a parking lot and partial routes. For the model a parking space is created at the incident locations of 100, 300, or 500 meters downstream of the nearest VMS. To guarantee a similar occurrence time for all incidents, an "incident vehicle" is placed at 100m ahead of the incident location at t = 900, assigned to park in the parking lot. The incident vehicle remains in the parking lot until 1500 seconds after detection, after this period the vehicle will be removed via the COM interface.

For the model it is chosen to incorporate the various incident locations by altering the last 500 meters of the model, i.e. move the incident location, instead of altering the location of the VMS. This is done because altering the location of the VMS would alter the input flow of the traffic when they activate.

4.4.2 Zone and Points Detection methods

The distances between the detection points will be simulated at 25, 50, and 100 meters. The detection systems are simulated with the help of detector points in VISSIM placed accordingly to their internal system distance, i.e. 25, 50 and 100m in front of the incident location. The detector points in VISSIM serve as the input for the COM interface.

4.4.3 COM Interface

The simulation model uses dynamic situations: different detection times, detection methods, increasing headway, and controlling the VMS with their according speed limits. This means the model needs to be dynamically controlled. This can be achieved by controlling VISSIM externally through the COM interface, for this research MATLAB has been used. The COM interface works by taking information during the simulation out of VISSIM, and sending back orders according to the nature of the received information. This back and forth is done for each second of the simulation. In this chapter the aspects that are controlled by the COM interface will be detailed.

Detection of the incident

The COM interface takes all the data from the detector points in VISSIM to determine if an incident has taken place. For the zone detection points this occurs as soon as the incident vehicle enters the parking spot. For the point detector systems this is detected by detecting a vehicle with a speed of <35 km/h over a detector. As detailed in paragraph 2.3.2 the AID system works with moving averages, this is also incorporated in the COM interface.

Adjusting Speed and Lane Closure

Besides adjusting the speed limits after incident detection, the COM interface also makes it possible to close of lanes for traffic. This is required in order to simulate the lane closure that occurs when an incident is detected. To simulate the arrow in the VMS, a lane closure is applied to the link. To simulate the cross, a partial route is enabled. This makes sure no vehicles pass the cross on the signs.

Increasing Headway

As detailed the headway increases surrounding the incident during the incident duration. In paragraph 4.2.3 it is found that the headway increases with a factor of 1.85, this means that during the incident the headway parameter CC1 is increased at 100m in front of the incident to a value of CC1=2.0.

Removal of the Incident

From paragraph 4.2.2 it shows that after detection of the incident the duration of a category 1 incident takes 25 minutes. The COM interface is used to remove the incident 1500 seconds after the incident has been detected. This needs to be programmed in the COM interface due to the variation in the detection time related to the detection method.

Routing Decisions

Aside from the above mechanics another important aspect of why the COM interface is used are the routing decisions that occur surrounding the incidents. Without routing decision vehicles approaching the incident would not overtake the incident vehicle. With the routing decisions it is simulated that the vehicles will not directly overtake the incident during the first 5 seconds. After this period, the approaching vehicles will try to overtake the incident vehicle by lane changing.

4.4.4 Simulations

After coding the COM interface it is now possible to start running the simulations to test the various detection systems under different scenarios. Five detection scenarios are created:

- Zone detection
- Point detection, distance 25 meters
- Point detection, distance 50 meters
- Point detection, distance 100 meters
- No standstill detection, i.e. only the MTM systems in place

These systems will be test with three different incident locations:

- Incident location : 100 meters
- Incident location : 300 meters
- Incident location : 500 meters

And three different I/C levels:

- I/C 0.7: 5021 pce/h
- I/C 0.8: 5796 pce/h
- I/C 0.9: 6521 pce/h

This leads to a total of 45 different simulation models processed through the COM interface. For each simulation 20 runs are performed, leading to a total of 900 run simulations. In chapter 5 the results of the model are discussed.

4.4.5 Explanation Experimental Model Setup

To give an insight in the experimental model, an event based description of the incident is created. The model has a built in “warm-up” period of 900 seconds. The warm-up period is used to ensure the model is filled with traffic, simulating a normal traffic situation. After these 900 seconds an incident vehicle is introduced to the model which will stop at the predetermined incident location.

Vehicles approaching the incident location will try to overtake the incident vehicle. The assumption is made that vehicles approaching in the first 5 seconds after the incident will not directly overtake the vehicle. It is assumed vehicles approaching the incident location are initially too distracted by the occurrence of the incident. These initial vehicles stop behind the incident vehicle before trying to overtake it. After this initial moment, the approaching vehicles and vehicles queued behind the incident vehicle look for a sufficient gap in the adjacent lane. When a sufficient gap is detected they overtake the incident vehicle.

With increasing I/C ratios the amount of gaps suitable to overtake the incident decrease; the queue behind the incident vehicle will grow faster. To explain this principle, imagine a one-lane road; when an incident occurs on this road, no vehicles can pass the incident location. The growth speed of the queue behind the incident vehicle is directly related to the flow of the upstream traffic.

On a road segment with two or more lanes, the vehicles have the possibility to overtake the incident vehicle. There is no longer a direct link between the flow of the upstream traffic, but rather a connection with the I/C ratio of the upstream traffic. At low IC ratios the approaching vehicles will have more room to overtake the incident vehicle. At higher IC ratios there will be less overtaking

opportunities due to the higher density; the queue will grow faster. This principle is supported by the findings in 61.

5

Model Results

Now that the model is calibrated, designed, and the simulations have been run, the results of the model can be analysed. This chapter serves as a summary of the found results and the methods used to derive and analyse the results. The main results that are discussed are the indicators from paragraph 4.3: Delay time, Queue length, Queue growth speed, discharge flow, Time to collision, Deceleration rates and the Detection time of the various systems. To increase the readability of this thesis, the result tables are displayed in Appendix A.

Median versus Mean

For the results of the model, both the mean and the median are available. In this research the median is used as the final indicator for the various results, mitigating possible extreme values of the model. The mean and the standard deviation are used in a student t-test to determine if the results from the models are significantly different from each other.

5.1 Detection times

The first results discussed are the detection times of the various systems. The detection time is deemed the most important aspect in relation to the other indicators (i.e. longer detection times leads to a larger life span of the bottleneck which directly affects the other indicators).

Incident time, Detection time and System detection time

To determine detection times of the various systems, two important points in time are needed; the point in time the incident occurs and the point in time the incident is detected. From now on these are defined as;

- Incident time, the point in time the incident occurs
- Detection time, the point in time the incident is detected

When subtracting these two points in time it takes to detect the incident can be calculated which is from now on defined as;

- System detection time, the length of time a system needs to detect an incident.

Results per I/C ratio

As discussed in paragraph 2.1.6, different I/C ratios lead to different shockwaves speeds, this has a direct relation to the detection time of the induction detection systems. To analyse the different systems a comparison is made per ratio.

Although the model is set up to minimize differences between incident locations, the results show different detection times dependant on the incident location. To determine if the results of the various incident locations are interchangeable, a t-test on the data is conducted with a significance level of a=0.05. The t-test is conducted on the different locations, i.e. 100m with 300m, 100m with 500m and 300m with 500m.

For the null hypothesis the following is taken:

H0=System time results from incident locations are not significantly different.

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	100.300	100.500	300.500	100.300	100.500	300.500	100.300	100.500	300.500
Zone det.	True	True	True	True	True	True	True	True	True
Point det. 25m	True	True	True	Reject	True	True	True	True	True
Point det. 50m	True	True	True	True	Reject	True	True	Reject	True
Point det. 100m	True	True	True	True	Reject	Reject	True	Reject	True
MTM	Reject	Reject	Reject	Reject	Reject	Reject	Reject	Reject	Reject
							A=0.05		

Table 26: Results from T-test, H0= System time results from incident locations are not significantly different.

The results show that too many H0 hypotheses are rejected. Because of the high level of H0 rejections results from the incident locations are not interchangeable, i.e. the systems are only analysed with each other within the same incident location. Because it is deemed that the system detection time influences other indicators used in this research, none of the other indicators are analysed between incident locations to compare the detection systems.

Comparison of the systems

The goal of this thesis is comparing the various detection systems, creating a comparison between costs and functionality. This question can be rewritten into a set of hypothesis tests for the systems, i.e. does applying a different system lead to significant different detection times. This is tested with the t-test with a significance level of 5%. Because the systems cannot be compared between incident locations, the t-test is performed per incident location.

The results of the t-test show that for the incident location at 100m, there is a significant difference for nearly all the systems. This excludes the 100m point detectors and the MTM system for the I/C ratios 0.7 and 0.8, and the 25m and 50m systems for the I/C ratios of 0.7. The lack of difference between the MTM system and the 100m system is expected due to the same detection distance of the incident. The lack of significant difference between the 25 and 50m detection with I/C ratio of 0.7 is due to the high standard deviation of the results.

The results show that with an increase in I/C ratio, a smaller detection time is found. Furthermore, an increase in I/C leads to a narrower band of results, i.e. the standard deviation decreases as well

as the median and mean converging to each other. It is theorised that this is due to the fact that an increase in I/C leads to less overtake opportunities that are affected by the random seeds.

Finally, it is seen that the detection of the incident is not directly linear with the distance. When looking at the median values, the detection times of the 25m and 50m systems seem to have detection time factor that at maximum doubles. The detection time between the 50m and 100m meter systems, have a detection time that higher than a factor of 3. This is explained by the setup of the model, which incorporates the assumption that the vehicles directly behind the incident do not instantly respond to the incident by lane changing.

The data suggests that with an increase in flow, the differences between the zone detection systems and the point detection systems decreases. For the differences between the point detection systems this is also visible. This can be explained to the decrease in lane changing opportunities due to the higher densities that occur with higher flows.

Results at low I/C ratios

In this research the decision was made to simulate I/C ratios: 0.7, 0.8 and 0.9. This was decided due to the absence of detection by the 100m systems within the 5 minute threshold. However, the high levels of chosen flows lead to small differences between the detection systems. The small differences suggest that the choice between zone and point detection is relatively nugatory when looking at the macroscopic indicators. The results show that the detection times, and thus the overall impacts, decrease with higher flows.

To investigate the detection times at lower flow rates a quick simulation is run with I/C ratios from 0.1 to 0.9 for which the results are displayed in *Figure 23*. Note, the results are meant to display an overall view of the detection times, this is done by displaying the median results and do not display the found standard deviation of the results. Furthermore, it is assumed that after 5 minutes, or 300 seconds the incident is reported manually to the traffic centre by (mobile) phone, hence the maximum detection time of 300 seconds.

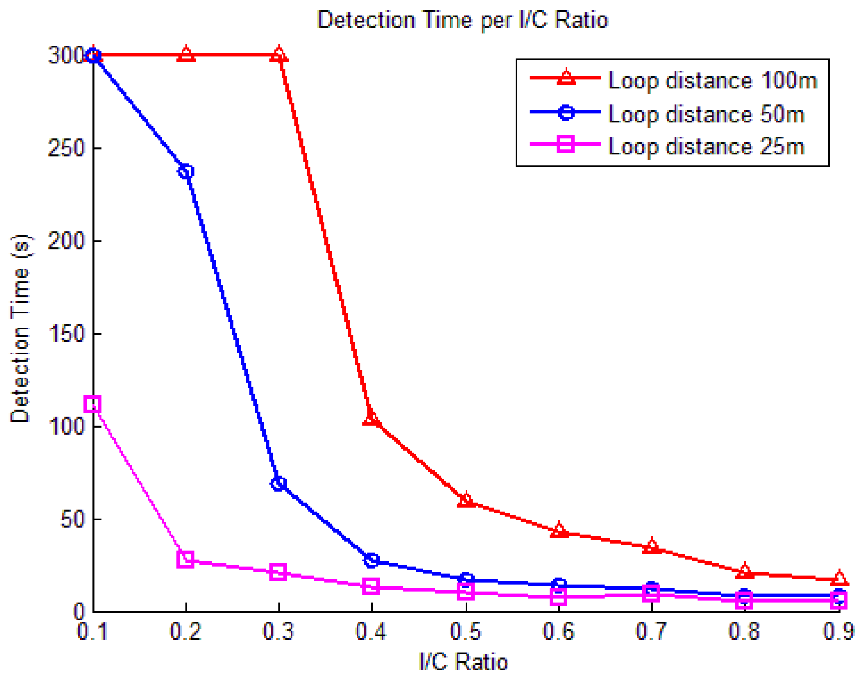

Figure 23: Detection time all I/C ratio

The results show a non-linear difference between the systems in relation to the I/C ratio. This becomes even clearer when plotting the differences between the systems as seen in *Figure 24*. It shows that the difference in detection time seems to be more exponential than linear. There also seems to be a "cut-off" I/C ratio from which the system begins to severely lose ground compared to the smaller spacing between detectors. For the spacing of 50m this seems to be I/C 0.3, and for the 100m system I/C 0.4. When comparing this to the zone detection systems, this means that the effectiveness of the point detective systems lose effectiveness in low flow rates, e.g. during the night time.

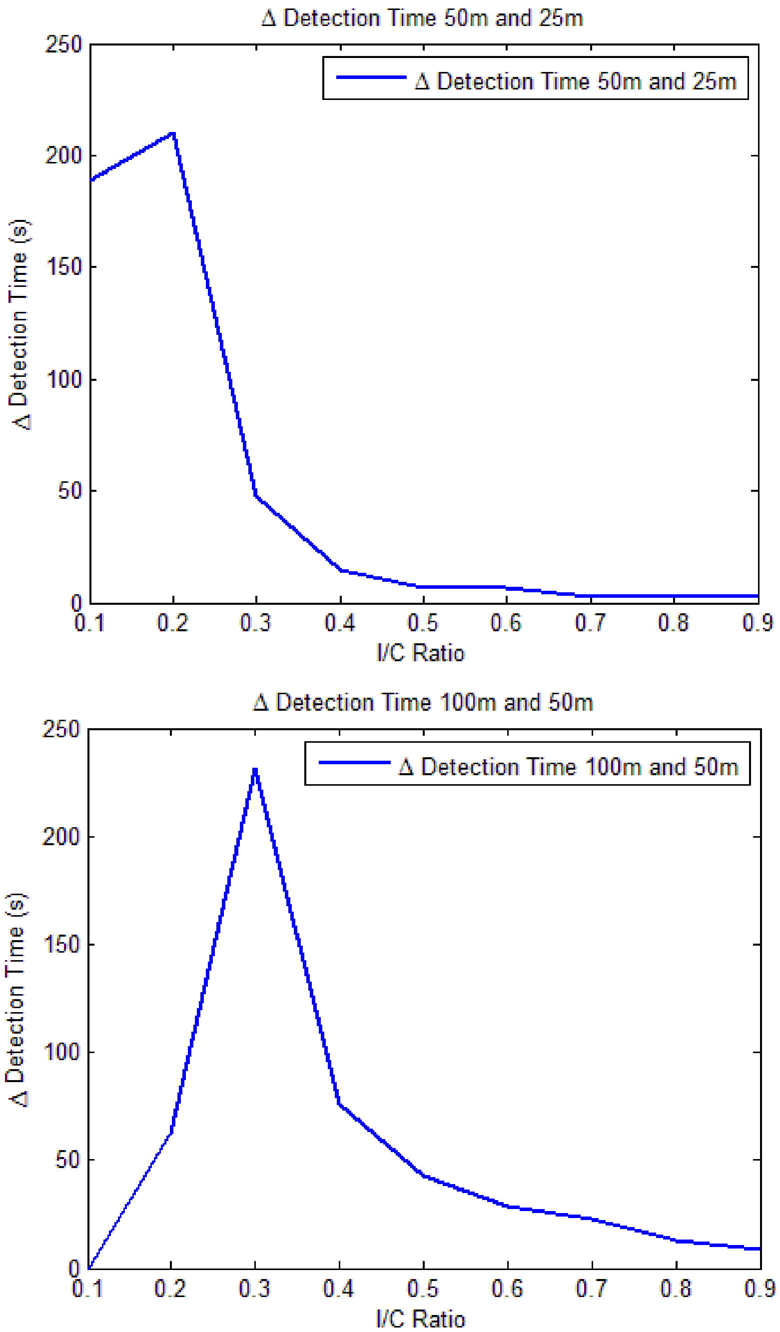

Figure 24: Difference in detection times with changing spacing

5.2 Undetected and Unwarned Vehicles

Besides the detection times of the system, the amount of vehicles that pass the incident location, without triggering the detection system, also gives an indicator on the level of detection. In this research these vehicles will be defined as the "undetected" vehicles. Furthermore, the simulation can show how many vehicles have passed the nearest upstream VMS of the incident, i.e. the amount of vehicles that will pass the incident location without knowing an incident has taken place. Note that for this research only the vehicles that pass the VMS after the incident are used for this category. With current technology, it is impossible to warn the vehicles that have already passed the VMS.

5.2.1 Undetected Vehicles

As with the detection times of the systems, the t-test shows there is no significant difference between the 25m and 50m systems at the I/C ratio 0.7. The MTM and 100m point detection systems do not differ significantly for I/C ratios 0.7 and 0.8. The differences between the 25 and 50 meter systems, although not significantly the same for the highest I/C ratios, practically do not alter that much from each other. This further suggests that on the high levels of simulated flow the differences between the 25 and 50m systems are not notably different.

5.2.2 Unwarned Vehicles

Another aspect in regards to the detection time is the amount of vehicles that pass the VMS before the interventions can be placed on the signals. This is especially of interest with tunnels in order to get an indication of how many vehicles enter the tunnel.

At the first incident location the same amount of unwarned vehicles are found for each of the three I/C ratios. Due to the increased headway zone, which reaches to the VMS, the maximum capacity of the zone is reached for all I/C ratios. As with the detection time and undetected vehicles, the difference between the systems decreases as the flow increases. When comparing the systems, the results show that for I/C ratio 0.7 all the following systems seem to not significantly differ, i.e. 25 compared to 50m and 50 compared to 100m.

The median of the 25m and 50m meters systems only slightly differ. The results show no significant difference between the 50m and 100m; this is due to the high standard deviation of the results. For I/C ratio 0.8 the 25m and 50m systems are negligible different, again underpinning the small differences in effectiveness between these two systems. For the I/C ratio 0.9 the difference between these systems becomes even smaller, due to the high intensity the I/C ratio 0.9 is the first in which we see a small difference between the camera system and the 25m system.

When looking at the other incident locations, the suggestion that the amount of unwarned vehicles is influenced by the increased headway zone seems to be affirmed. With a larger distance between the incident and the first VMS, the amount of unwarned vehicles increases with the flow. When comparing the various systems, it shows that the differences between the 25m and 50m systems are small compared to the 50m and 100m systems. When extrapolating the difference between the 25m and 50m systems, the 100 meter systems come off as a worse option.

For the incident location 500m, the same insight is gathered as from the incident location 300m. The difference is visible for the 100m detection systems at the two highest flows. The results show larger differences when comparing it to the 50 meter systems. The congestion, having an effect on the traffic near the VMS, is deemed responsible for this. This is supported because at the 500m system it takes longer for this to happen, i.e. the traffic flow upstream has a longer stretch of road in which it is unaffected by the incident. This means a larger amount of vehicles can pass the VMS unaffected.

5.3 Queue Length

Besides the directly measurable characteristics of the systems, i.e. detection times and passed vehicles until detection, this research also focuses on the effects on indirect indicators. The first is the queue length that occurs due to the incident. In this paragraph the results of each of the systems are displayed and analysed.

As done in the previous paragraph, first the results are displayed per I/C ratio, as I/C ratio is deemed the biggest influence that is responsible for the maximum queue length. To compare the results of the various systems, a t-test is conducted to determine if a different system leads to significant different results.

For the maximum queue length an interesting result is found; for all I/C ratios the t-test shows that for all the systems, with exception of the MTM systems, the results do not significantly differ from each other. The MTM systems show a comparable result for the incident location at 100m in which the detection systems do not differ from the MTM system. For the incident locations at 300 and 500 meter there is a significant difference between the MTM system and the other detection systems.

From a practical perspective the maximum queues do not differ greatly between the systems.
Although a longer detection time means a longer incident time, i.e. bottleneck time, the difference in systems detection time between the detection systems is 0 to 41 seconds. When comparing this to the total incident time of 1500 seconds, this only makes a maxim of approximately 3% of the total time.

5.4 Queue Growth

Besides the total queue length, the queue growth speed is another indicator that can be analysed. The queue growth speed is especially useful to determine the time it will take the congestion to reach: tunnels or off- and onramps. The summarised results can be found in the Appendix.

Incident location = 100m

The results show that after the queue has reached approximately 1000m, the type of system no longer influences the queue growth speed, i.e. it follows the standard shockwave speeds, and therefore the focus is put on the first 1000 meters of the queue growth. The results from the t-test however show that there is only a significant difference between the zone detection systems and the slowest systems at the 500 meter mark. In contrast to the expectations, the faster systems create a queue growth that is higher than with the slower detecting systems. An explanation is the fact that the faster systems force the traffic to lower maximum speeds, lowering the road capacity

which leads to faster congestion forming. At the 1000m meter mark, a convergence is visible for the various detection systems on the higher levels of flow. For the lowest simulated flow the zone detection system makes a transition from being the system that generates the fastest growing queue towards the second slowest system. The MTM system and the 100m point detection systems remain the systems with the slowest growing queues. However the t-test does show that all the systems, for all flow levels, do not have significantly different results.

Incident location = 300m

As with the incident location= 100m, a higher degree of differences between the queue growth speeds, at the lowest flow, is seen. Due to the higher level of system times of the MTM system, the differences between the queue growth speeds become more visible. At the time moment t=60, the graph shows a clear distinction in queue growth between the slower systems and the faster working systems. Although the higher levels of flow show a separation of the queue growth speeds at different queue lengths, the time in which this occurs can directly be traced back to the activation of the VMS. In contrast with the 100m incident location the zone detection system stays the system with the fastest queue generation.

Incident location = 500m

The queue growth for the farthest incident location gives a similar type of result as the previous incident locations; the slowest system generates a queue growth that is significantly slower than the fastest systems. From this third simulation the theorem that slower systems generate slower growing queues appears to hold up. It should be noted however, that after each system has activated it first VMS the queue growth speed seems to stay stable between the systems. This becomes visible when extending the graphs to 2500 meters, concluding that the biggest effect the systems have on the traffic focusses mainly on the period up to the activation of the first VMS, hereafter the queue is not influenced to a significant extent and forms itself as a normal queue. This is displayed in Appendix A.

5.5 Discharge Rates

The final macroscopic indicator of traffic flow is the discharge rates. To analyse the found results, the discharge rates are split up into different stages of the incident:

- Period 1: **Normal flow – Incident**; the normal discharge flow
- Period 2: **Incident – Activation VMS**; discharge during the incident before the activation of the VMS.
- Period 3: **Activation VMS – Activation VMS+ System detection time**; discharge directly after the activation of the VMS, this is done in order to determine the direct influence of activating the VMS.
- Period 4: **Activation VMS – Removal of incident**; the discharge during the incident until it is removed.
- Period 5: **Removal of incident – End of Simulation**; discharge after removal of the incident.
- Period 6: **Incident – Removal of incident**; average discharge over the whole incident duration.

From the results it shows that there are several time periods that have the same practical discharge rates, and that the type of system has no practical influence on the discharge rates. These time periods are; Period 1, Period 4, Period 5 and Period 6.

For Period 1 this is expected as the incident has not occurred and each system is tested with the same model. For Period 4 the differences, although sometimes significantly different, have a very small difference; each simulation has an internal absolute difference that has a maximum of 0.5% in difference. Combining this with low standard deviations this gives the ability to confidently conclude that the detection systems do not have an influence on the discharge during this period.

Period 5 shows the same form of results as period 4; although the results are sometimes significantly different, the practical differences are negligible. The differences for each system vary less than 0.5% per flow simulation and have a maximum difference of 1% when comparing the different flows to each other. Again these results show low standard deviations, giving the possibility to confidently conclude that the systems do not have an influence on the discharge during this period. Finally, the same applies for Period 6, i.e. the discharge during the whole time stretch of the incident, for this period the maximum difference for each flow input is capped at 1%. Note that although the discharges may be the same, the length of the periods does alter due to the system detection times.

The remaining periods are Periods 2 and 3. These periods are influenced by the system times of the various detection systems, i.e. Period 2 is comprised of the system detection time added with the 60 seconds handling time. Period 3 has the same length, but consists of the same time period after the activation of the VMS. These periods are chosen to get an insight into the effect the activation of the VMS has on the discharge.

The results show that activation the VMS coincides with a decrease of the discharge. This occurs for all the systems, I/C ratios and incident locations. When comparing the systems to each other we find that the faster systems have a higher discharge during Period 2, this relation is visible for all I/C ratios and incident locations. When applying the t-test the result shows that there is only a significant difference between the results of the MTM and 100m systems when compared to the

zone and 25meter systems, again this is due to the high levels of standard deviations that occur from the simulations.

For Period 3 an inverse relation is found for the discharge at the incident locations of 100 and 300 meter; the faster systems give a lower discharge during this period. For the incident location at 500 meter there seems to not be a direct link between the type of system and the discharge. The results from the other periods showed that there was a negligible differences in the discharge, thus the discharge levels out after Period 2 and 3.

5.6 Delay

Due to the dynamic nature of the model, in which lanes get closed and speed limits get adjusted, it is not possible to directly get the delay values out of VISSIM. The microsimulation program does not see the lower speed limits as delay. To calculate the delay for the simulations, first a simulation is run without any interference of the incident or any lowered speed limits. This is done per I/C and the results are visible in *Table 27*.

	I/C ratio		
Model	0.7	0.8	0.9
Incident location 100m	339	355	414
Incident location 300m	340	355	414
Incident location 500m	340	355	414
Median	340	355	414

Table 27: Travel Times (s) for distance = 9500 meters

As expected higher I/C ratios lead to higher travel times, where the highest increase is found between the 0.8 and 0.9 ratio. This as expected when looking at the I/C ratios and their related descriptions in paragraph 2.1.5; at I/C ratio 0.9 congestion structurally forms with still standing queues, without external disturbances.

From the median travel times, time of entry, and the time of exit, i.e. the travel times, the delay can be calculated per vehicle. The method used is derived from the congestion and delay theory in paragraph 2.1.4.

The vehicles entering the network are represented by the blue line. The green line represents the time takes vehicles to exit the network without interference. The red line is the actual measured number of vehicles leaving the network. The delay is represented by the area between the green and red line. Note that according to the figure, the first vehicles enter the system at t=300 seconds, this is due to the start-up time of the model, which is needed in order to “fill” the model.

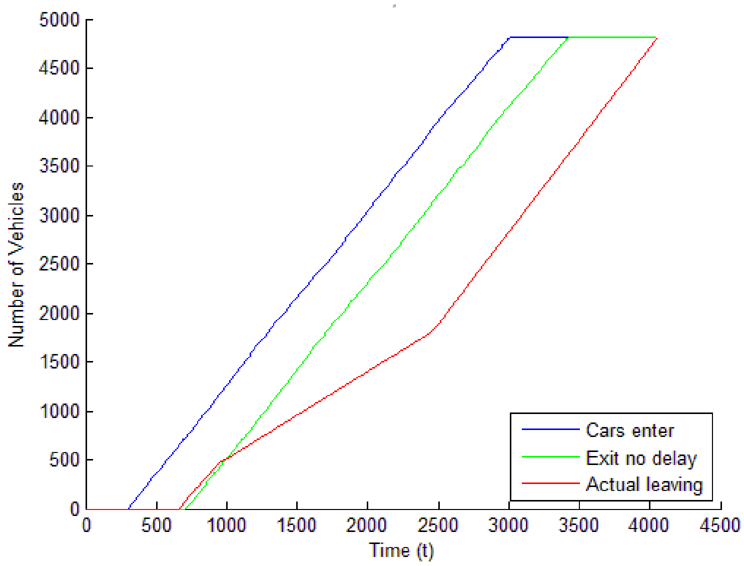

Figure 25: Vehicles Entering and Leaving Network

Incident location = 100m

With the above described method, the various results of the model are calculated. To view the results, see Appendix A. When looking at the results a clear increase in delay is visible with an increase of the flow; this is found for all systems and all incident locations. When looking per incident location, the result for incident location = 100m seem to show an increase in delay as the detection systems become slower, i.e. have a larger system time. The exception is the 50m system at I/C ratio of 0.9. Furthermore, at I/C ratio 0.7, the MTM system has a lower median compared to the 100m system. However, if we apply the t-test none of the results found are significantly different from each other, with except of the MTM system at I/C ratio 0.8;

Incident location = 300m

At incident location =300m, the results do not give a clear pattern in regards to the delays and the method of detection. At the lowest flow levels, the 100m detection system appears to have a lower delay time than the faster reacting 25m system. At the I/C ratio of 0.8, the 25m and 50m detection systems have a lower delay time than the zone detection system, but when finally looking at the highest flow levels, the fastest reaction systems do get the lowest delays. This randomness can be explained by the high levels of deviations inside the data, which also leads to the absence of significant differences between the results. Note that the MTM systems do provide significant different results compared to the other systems, but this is due to the high distance of 300 meters to the MTM system. Apparently 300 meters is a high enough distance in order to get significant different results for the delay.

Incident location = 500m

At I/C ratio 0.7, the faster reaction systems provide lower delay times. However, for the I/C ratios of 0.8 and 0.9 this does not hold up. For I/C ratio 0.8, the zone detection system gives a higher delay than the 25m detection system, for the I/C ratio of 0.9 the 50m detection system has a higher delay than the 100m system. After conducting the t-test all the results again do not seem to differentiate from each other significantly.

Overall, the results from the delay give an overview in which the choice of the standstill detection system, at high flow rates, does not influence the delay significantly.

5.7 Safety Aspects

Before the safety indicators, TTC and Deceleration rates, can be analysed, a few considerations have to be made. The first important consideration is the location in which the safety aspects will be measured. Second, the consideration of the time period, in which the safety aspects will be measured, needs to be made. The underpinning for choosing these two considerations will be detailed in the segment below.

Location

For the area in which the safety aspects are measured, the data from the model gives two possibilities; either solely looking at the first 100 meters upstream of the incident, or looking at the area up to the first VMS. Both can be argued to be adequate sections to analyse the data on. Purely looking at the section surrounding the incident gives a focus of the safety aspects mostly surrounding the incident. The found TTC-values and critical deceleration rates are directly related to the incident itself, and vehicles switching lanes in order to avoid the incident. The section up to the VMS gives a broader view, i.e. it also includes the approaching the incident location.

Choosing a section too small can lead to too small measurements, choosing the section up to the first VMS leads to variable measurements between the incident locations. However, in paragraph 5.1 it was chosen that the results of the various incident locations cannot be directly compared with each other. Therefore, for the location a variable section can be chosen for the analysis. Note that it is very important not to misinterpret the data by comparing the different incident locations.

Time Period

In the paragraph 5.4 it was found that the traffic has a homogeneous queue growth for all the systems until the VMS gets activated, i.e. sixty seconds after the detection of the incident. For the time period measuring traffic safety aspects the same is assumed, i.e. there is no difference in the safety indicators until the VMS is activated. To compare the systems with each other, the time period is chosen from the time of the incident up until the VMS gets activated by the slowest respond detection system. By combining the two considerations of location and the time period, a table is constructed. The table is constructed by adding 60 seconds onto the system that has the highest system time, i.e. a detection time of 124 seconds, for the incident location = 300, gives a time period in which the safety aspects will be measured of 184 seconds. The results for each I/C ratios and incident location can be found in Table 28.

To only analyse the increase, or decrease, of the safety aspects in regards to the detection of the incident, a “null” measurement sample is taken (at t=850). If the time period measured is 147 seconds after the incident, the null measurement is taken from t=703 to 850 seconds. From tests it showed that the type of system has no influence on the “null” measurement; only one null measurement is needed per I/C and incident location.

	I/C Ratio		
Location	0.7	0.8	0.9
Incident Location = 100m	91 s	89 s	87 s
Incident Location = 300m	184 s	147 s	137 s
Incident Location = 500m	278 s	217 s	184 s

Table 28: Time periods for safety aspect measurements

5.8 Time to Collision

The first safety aspect that analysed is the Time-to-Collision (TTC). To iterate the theory from paragraph 2.2.3; the TTC is calculated by dividing the distance between the following and leading vehicle by the difference in speed between the leading and following vehicle. In the theory it is described that if the calculated TTC is below the critical TTC value (set at 4.0 seconds), it is defined as a conflict.

From the above and the equation for the TTC, it can be deduced that to calculate the TTC-value the distance to the leading vehicle and the difference in speed is required. Although VISSIM gives the possibility to record these characteristics of each vehicle, initial investigations showed that the distances recorded by VISSIM were not accurately describing the distances between leading and following vehicles.

To solve this, a script is created which calculated vehicles distances based on link-coordinates. After completion of the script, significant differences were found with the initial VISSIM data. For the further analysis of the TTC values the newly found, calculated by script, distances are used. The same method was applied on the speed differences; however, after completion, the script did not show significant differences for the speed differences between the vehicles, therefore the initial VISSIM data is used for the speed differences.

As described in paragraph 5.7 the time period and location of the measurement vary per incident scenario, therefore the systems will be analysed per I/C ratio and per location.

Incident location = 100

To analyse the effects detection systems have on the traffic, first a “null” measurement is performed on the traffic. As described in paragraph 5.7, the null measurement is taken from the period at t=850 and backwards with the corresponding time period, in which the actual safety aspects will be measured. The results can be found in the Appendix.

The incident has a negative effect on the safety; more vehicles are below the TTC-critical threshold in both percentage and absolute time periods. When comparing the systems to each other there is no significant difference found between the systems after applying the t-test. Furthermore, there is no clear indication the speed of the systems has any influence on the percentage of TTC.

Incident location = 300m

In the null measurement an increase is found, this is expected as the measurement period and size of the measurement area is increased for this incident location.

The results for the incident location = 300m, give a slightly confusion view. The data suggests that the slower systems have a lower percentage of vehicles under the TTC – critical threshold. This also holds up when applying the t-test. However, at the highest I/C ratio the data also suggests that the incident has a positive effect on the traffic safety. It can be deducted that there is an error present in the null measurement or the actual incident measurements of the model.

When taking the absolute time steps below the threshold, this view is undone. Here the median data results show an increase in absolute time steps with the slower systems. However, when

applying the t-test the results do not show significant differences between the systems due to the large standard deviations.

Incident location = 500m

When looking at the null measurement a big difference is noticeable compared to the other incident locations. Although the time period and the size of the measurement section are increased, the results show a drastic decrease in the percentage and absolute values of the TTC. It is at this time unknown to as why the null measurement for incident location = 500 gives such extreme differences when compared to the other two locations. This can only be appointed to an inherent, undetected flaw in the model.

When analysing the results, it shows that with an increase in system times of the various systems, the number of time steps in which the critical threshold gets exceeded increases. Furthermore a decrease in the standard deviation is witnessed with an increase of the flow. When analysing the results with the previously used t-test, the results for each of the MTM systems gives significant different results compared to all the systems in all the I/C ratios. For the lowest I/C ratio the results of the absolute time steps of the zone, 25m and 50m detection systems do not alter significantly from each other. At I/C ratio 0.8 the 25m and 50m point detection system also do not differ significantly from each other. Finally at the highest level the 25m detection system does not alter differently from the zone detection and the 50m detection system.

5.9 Time Integrated TTC

As explained in paragraph 2.2.3 merely using the number of TTC exceedance levels does not directly give an indication of the safety. For instance a TTC value of 1 second is deemed more dangerous than a TTC value of 3.9 seconds, although the above analysis does count both instances as a conflict situation. Hence, this paragraph analyses the Time-Integrated-TTC (TIT). In this analysis the TIT has been recalculated to show the results in seconds instead of time steps.

Incident location =100m

For the lowest I/C ratio there is an increase of TIT visible for the systems, albeit that due to the high standard deviations none of the systems show any significant difference in the results between the systems. For the I/C ratios of 0.8 and 0.9 there is no such trend visible.

Incident location =300m

For the results at incident location = 300, there is no visible trend which ties the detection of the system with the level of the TIT. Furthermore none of the systems show significant differences between them.

Incident location =500m

As with the TTC value the incident location = 500, the null values depict extreme low values compared to the other incident locations even though the measurement location and time period is longer with this incident location.

The results show a trend in which the slower reaction systems lead to higher TIT values. When applying the t-test, the results show that for the I/C ratio = 0.7 the detection systems do not show significant differences compared to the next two levels of detection systems, i.e. the zone compared to the 25 and 50m systems. This applies to all the systems the MTM detection. For the I/C ratio = 0.8 all the results show significant differences, excluding the 25m system when

compared to the 50m system. For the highest flow the three fastest reaction systems do not show significant differences between them, the slowest reaction systems however do give significant different results.

5.10 Deceleration

The next safety aspect analysed is the amount of time steps vehicles have a deceleration exceeding the critical value set at 4 m/s^2. For the Time-To-Collision VISSIM did not always give feasible results regarding the leading vehicles and distances between them. To make sure VISSIM did not give false deceleration rates a script was created using the individual speeds per time step in order to determine the deceleration rates. As suspected, since the deceleration rate is not dependent on other vehicle data, the given results in VISSIM were correct and did not have to be altered.

Incident location =100m

The results show the systems have very small effects on the amount of time steps below the threshold for the lowest flow. This also shows when applying the t-test; none of the results show significant difference between them. For the higher flow levels the results neither show significant different results. However, it seems for the 0.8 systems the amount of time steps below the threshold is lower. Furthermore the I/C ratio = 0.8 seems to have significant higher standard deviations compared to the other two ratios.

Incident location =300m

Unlike the TTC, the percentage of decelerations above the threshold seems to increase with the increased null measurement time and section length; however, the found null measurement results are still close to zero, at first glance suggesting a normal traffic flow.

The results show an increase of percentage from the zone detection system compared to the point detection systems. However, the MTM system gives the least amount of percentage of time steps below the threshold. When looking at the absolute values it shows that the absolute amount of time steps increases including the MTM systems. The lower amount of percentages comes due to the higher level of discharge that occurs with the MTM system.

At the incident location = 300m, the above trend of the increasing amount of time steps exceeding the threshold does not apply. The two slowest reaction systems however do still have the highest absolute number of time steps. The zone detection and the 50m point detection systems both however come out as the more unsafe system.

At the highest flow level, there is no visible trend in which system achieves the highest level of safety. The zone detection system has less time steps exceeding the threshold than the 25m and 50m detection systems. However, percentage wise all three are worse than the 100m and MTM system. When using the t-test all the systems do not show significant different results, except the zone detection system compared to the MTM system at I/C ratio = 0.8.

Incident location =500m

The null measurements again show a low occurrence of threshold exceedance, apparently measuring the deceleration rates during normal flow gives more expected results than the TTC safety indicator.

At the incident location = 500m the results, although not significantly, show an increase of the absolute number of time steps as the reaction time of the system increases. When analysing the percentage of time steps, this does not hold up, due the difference in discharge. When comparing the different flow rates the number of absolute time steps exceeding the threshold the absolute values decrease as the flow rate increases. When investigating the other incident locations this also seems to occur. A possible explanation for this phenomenon is that with a lower flow rate the vehicles have more space to change lanes leading to more lane changes, leading to higher deceleration rates.

5.11 Conclusions

The overall goal of simulating the incidents and the surrounding processes was to give a quantitative comparison of the effects the detection systems had on the traffic flow and safety. The overall conclusion of this chapter is that the simulations did not reach its goals; either there is not a noticeable difference found, or the high standard variation found within the simulations diminishes the conclusiveness of the results.

Although the high variance led to non-significant differences, the detection times and undetected vehicles seem to be the only indicators that showed a practical differences between the results. The results show that the detection time is not linearly related to the distance between the detector points. With the point detection systems this is due to the possibility of vehicles passing the incident. Higher flow rate result into a converging of the results, i.e. the differences in detection time between the detection systems decrease as the flow increases. The non-linear relation between detection distance and detection time is further supported by the quick analysis with lower flow rates; the relation seems to be exponential rather than linear.

The macroscopic indicators did not show significant or practical differences between the results. The absence in difference is due to the high flow rates; the differences in detection between the systems get nullified by their share of the total incident time. The maximum difference between the 'fastest' zone detection systems and the 'slowest' point detection system with detectors spaced at 100m is 41 seconds. Although the detection time difference does have a practical influence in regards to the amount of vehicles that pass the incident undetected the 41 seconds are negligible in the total incident time of 1500 seconds. Another influence that affects the differences in impact the system detection times have on the macroscopic indicators is the fact that it takes 60 seconds after detection for the mitigations to be implemented. This is visible in both the identical queue growth speeds of the systems and the identical discharge rates registered up to the moment the VMS get activated.

Regarding the safety aspects of the simulations the same conclusion as with the macroscopic results can be reached. The results show an overall non-significant difference between the detection systems. The reason behind the inaccuracy of the models' result can partly be addressed to the nature of the conducted tests, and the setup of the research leading up to the simulation. For the calibration of the model a rough calibration was performed on the basis of 4 parameters and the discharge measured. However, in an incident there needs to be a lot of more input in order to get a more realistic view of the reality. This is addressed in the recommendations.

6

Detector Choice per Situation

The goal set out at the start of the research was to create recommendations on the choice of standstill detection systems per traffic scenario. This chapter combines the simulation results and the found criteria to create recommendations on three different traffic location scenarios; tunnels, hard shoulder running and bridges. Although chapter 5 shows that the results found from the microsimulation model do not give significant results, it did show that the differences in system detection times are related to the I/C ratios.

Implementing Microsimulation results into flow chart

Before the three traffic scenarios will be analysed, it is necessary to input the results from the simulation into the flow chart designed by (Martin, 2003). The simulation results should be considered after the step considering if the detectors are applicable in the location. The costs should be considered knowing which impacts the systems have on traffic flow and safety. In the evaluation of the different traffic scenarios, the model results will be evaluated on detection time.

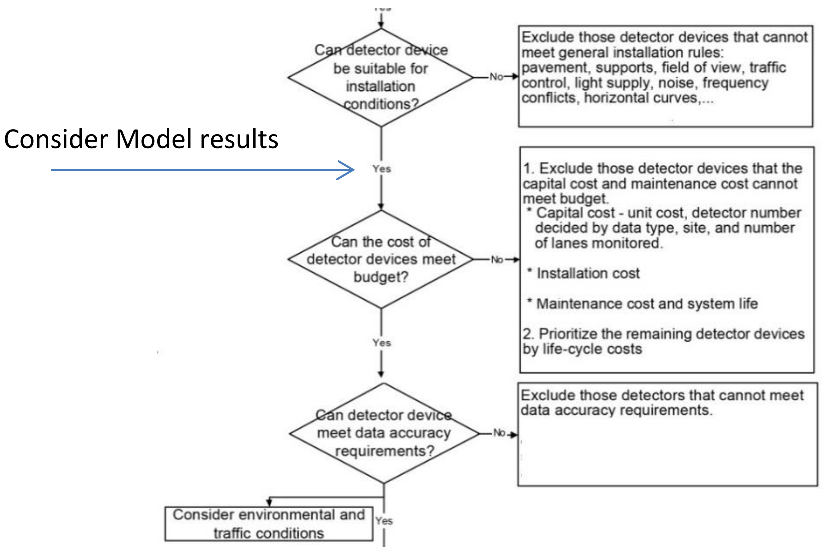

Figure 26: Implementing model results

Flow Chart Criteria

In this chapter the three traffic situations serve as the input for the flow chart displayed in paragraph 3.2. From the flow chart the following criteria have been selected:

- Can the system detect all required data?
- Is the system usable as a standstill detection system?
- Can the system be installed on the location?
- Which system has the lowest EAC?
- What is the detection speed of the system?
- Is the system affected by environmental impact present at the location?
- Does maintenance disrupt traffic flow?

Note that the chosen criteria are subject to alterations. Decision makers should try to distinguish more possible criteria when applying it to their project. A possible addition for instance is the systems' capability to work in changing lane configurations.

In the next paragraphs for each of the traffic situations (tunnels, bridges, hard shoulder running) the above criteria questions will be discussed. This chapter should be seen as a global overview of which considerations, guided by the criteria, are relevant to the specific traffic scenario.

6.1 Tunnels

Tunnels are the first considered traffic situation, in tunnels the following points are of relevance.

Can the system detect all required data?

From paragraph 3.2.1 it showed that:

- Inductive loops can detect all data except non-inductive blockades.
- Active Infrared systems can detect all data except: occupancy, presence and other blockades.
- Passive infrared system cannot detect speed unless there are multiple detection zones.
- Radar systems require movement to detect presence and cannot classify vehicles
- VIP systems can detect all data

Is the system usable as a standstill detection system?

Passive infrared systems are used as presence detectors due to their incapability to detect speed, this makes the system unsuited for standstill detection. All other systems can be used as standstill detection systems; the AID system is however not able to fulfil this task satisfactory due to its low detection speed.

Can the system be installed on the location?

In tunnels all the systems can be installed. Because the tunnel negates the need for supportive structures, it is an excellent installation location for all systems.

Which system has the lowest EAC?

The height of the tunnel limits the field of vision for VIP systems, requiring more to be installed. However, because the systems can be installed on the tunnel itself, no extra costs are required for the supportive structures; decreasing the costs of the systems. Hence, in tunnels VIP have the lower EAC. The active infrared systems are the most expensive solution. An indication of the costs can be found in paragraph 3.2.4.

What is the detection speed of the system?

The speed of detection for the point detection systems is directly related to the total cost. By increasing the amount of detection points the detection speed increases. The results of the model show that the I/C ratio directly determines the detection speed, displayed in paragraph 5.1. Because VIP systems are zone detection systems, they have the fastest detection time. In tunnels it is preferred to have a fast detection; smallest detector spacing distances are recommended.

Is the system affected by environmental impacts present at the location?

A tunnel is a semi closed environment; inside the tunnel there is no direct influence from the environment. Because the system is sheltered from the outside environment, the negative effects of the environment has on VIP systems is diminished.

Inside the tunnel radar detection systems are known to have a high error ratio due to reflections in the tunnel. Furthermore, at tunnel entrances heavy precipitation interferes with the radar systems; making the system not preferred in tunnels.

Does maintenance disrupt traffic flow?

It is not possible to maintenance any of the systems without disrupting the traffic flow due to the tunnel's closed environment. Maintenance of inductive loops will however take longer than for the other systems. The same applies for the installation of the systems.

Score sheet

From the above reasoning, the following score sheet is created for the systems. The systems are ranked from -2 up to +2. Some of the criteria are "knock-out" criteria, when a system is no longer eligible for use a "Does not Qualify" (DNQ) will be applied.

	Inductive Loop		Radar	Infrared		VIP
	AID	SSD		Active	Passive	
Data Collection	+	+	0	+	- -	++
Usable as standstill det.	-	++	++	++	DNQ	++
Installation location	++	++	-	++	+ +	++
Equivalent Annual Cost	++	0	0	- -	+	++
Speed of Detection	- -	+	+	+	- -	++
Affected by Environmental	+ +	+ +	-	+	+ +	+
Installation & Maintenance	0	0	+	+	+	+
Total	+4	+8	+2	+6	DNQ	+12

Table 29: Detector Score Sheet for Tunnels

The score sheet shows that VIP systems score the best in tunnels; this is mainly due to the absence of environmental impact inside the tunnel. Inductive loops are ranked second due to the lower detection speed and higher costs. Radar systems fall behind due to the interference of the tunnel location on performance.

6.2 Bridges

For bridges the following criteria have to be considered.

Can the system detect all required data?
Data detection is independent of the traffic situation, see paragraph 6.1.

Is the system usable as a standstill detection system?
Passive infrared systems are not able to detect individual vehicle speed in situations with more than one lane, making them unfit as standstill detection systems. The AID system is not recommended due to the high detection time.

Can the system be installed on the location?
On concrete bridges all detection systems can be installed. However, the reinforcements in the bridge may influence the performance of the inductive loops. On iron bridges only inductive loops cannot be installed. As opposed to the tunnels, the type of bridge design determines the need for supportive structures.

Which system has the lowest EAC?
Unlike tunnels, there is no height limitation for the VIP systems, however supportive structures are required. For an indication of the EAC, see paragraph 3.2.4.

What is the detection speed of the system?
The detection speed is independent of the traffic situation, see paragraph 7.1.

Is the system affected by environmental impacts present at the location?
Bridges are not a closed environment; the detector systems are exposed to environmental influences such as: temperature, wind, light, and shadows. This makes the VIP systems score the lowest on this criteria. Active Infrared systems are affected by heavy precipitation.

Does maintenance disrupt traffic flow?
The disruption of traffic during maintenance depends on the characteristics of the bridge, i.e. can workers reach the system or not. Inductive loops always disrupt traffic flow during maintenance.

Score sheet

From the above reasoning the following score sheet is created for the systems. The systems are ranked from -2 up to +2.

	Inductive Loop		Radar	Infrared		VIP
	AID	SSD		Active	Passive	
Data Collection	+	+	0	+	- -	++
Usable as standstill det.	-	++	++	++	DNQ	++
Installation location	+(1)	+(1)	+(2)	+	+	++
Equivalent Annual Cost	++	0	0(2)	- -	-	+
Speed of Detection	- -	+	+	+	- -	++
Affected by Environmental	+ +	+ +	+ +	+	+ +	- -
Installation & Maintenance	0	0	+	+	+	+
Total	+4	+7	+6	+6	DNQ	+8

Table 30: Detector Score Sheet for Bridges

(1)On Iron bridges inductive loops cannot be applied.

(2) The design of the bridge, more specifically the possibility on overhead system placement, determines the score

For radar systems the design of the bridge greatly determines the feasibility of the systems. If the bridge does not allow overhead positioning of the radar systems, the radar systems become an unfit solution for standstill detection.

6.3 Hard Shoulder Running Lanes

The final considered situations are the hard shoulder lanes. For the hard shoulder running the following criteria are considered.

Can the system detect all required data?

Data detection is independent of the traffic situation, see paragraph 6.

Is the system usable as a standstill detection system?

Passive infrared systems are not able to detect individual vehicle speed in situations with more than one lane, making them unfit as standstill detection systems. The AID system is not recommended due to the high detection time.

Can the system be installed on the location?

There are no limitations for any of the systems regarding installation. However, the radar systems require overhead positioning in order to measure individual vehicle characteristics; requiring a gantry. This would mean that, for the system to function as a standstill detection system, gantries are required every 25, 50 or 100 meters; deemed as unpractical. Therefore, the radar systems are deemed unfit as standstill detection systems on hard shoulder running lanes.

Which system has the lowest EAC?

Unlike tunnels, there is no height limitation for the VIP systems; they still remain the cheapest option. However, as with the bridges, supportive structures are required. For an indication on the EAC, see paragraph 3.2.4.

What is the detection speed of the system?

Hard shoulder running lanes are a special scenario; the lanes are only opened at peak hours. This means that the lanes are not subject to the lower I/C ratios. This means the differences in detection times is small; meaning a medium spacing between the detector points would suffice.

Is the system affected by environmental impacts present at the location?

Hard shoulder lanes are not a closed environment; the detector systems are exposed to environmental influences such as: temperature, wind, light, and shadows. This makes the VIP systems score the lowest on this criterion. Infrared systems are affected by heavy precipitation.

Does maintenance disrupt traffic flow?

Infrared and VIP systems can be placed besides the hard shoulder, requiring no interruption of the traffic during maintenance. Radar systems are placed above the road, during maintenance a lane closure will have to be applied although briefly. For inductive loops the lane closure will be of a longer duration.

Score sheet

From the above reasoning the following score sheet is created for the systems. The systems are ranked from -2 up to +2.

	Inductive Loop		Radar	Infrared		VIP
	AID	SSD		Active	Passive	
Data Collection	+	+	0	+	- -	+ +
Usable as standstill det.	- -	+ +	+ +	+ +	DNQ	+ +
Installation location	+ +	+ +	DNQ	+ +	+	+ +
Equivalent Annual Cost	++	0	- -	- -	+	+
Speed of Detection	- -	+	+	+	- -	+ +
Affected by Environmental	+ +	+ +	+ +	-	+ +	- -
Installation & Maintenance	0	0	+	+	+	+
Total	+2	+8	DNQ	+4	DNQ	+8

Table 31: Detector Score Sheet for Hard Shoulder Running Lanes

Due to the overhead positioning requirement it shows that the radar systems become an unfit method of detection. The score sheet indicates the VIP and inductive loops are relatively equal due to the environmental influence on the VIP systems.

6.4 Advancement in Technology

From the evaluation of the various detection systems, it shows that VIP systems have the potential to be the best detection systems. Although the VIP systems score the best in regards to cost and functionality, the environmental impacts on the VIP systems lower its overall scores. However note that in comparison to inductive loops, VIP systems are a fairly young solution; advances in the technology may negate the environmental influences of the camera systems.

7

Conclusions

The objective of this research is to give insights into the relation between: costs, functionality, and the influence of a specific system on traffic flow and safety, for the various off-the-shelf detection systems available in the Netherlands. This chapter presents the findings and conclusions, based on the research questions formulated in chapter 1, in order to fulfil the aforementioned objective.

In order to determine the functionality of the various detection systems, answering research question 1, criteria are distilled from: found literature, regulations, and the conducted stakeholder interviews. After an analysis of the parties involved, the three most important stakeholders are deemed: Rijkswaterstaat, provinces, and traffic centre operators. The found criteria are displayed in chapter 3.2 and can be divided into four categories: functionality, costs, traffic flow, and traffic safety. Furthermore, it is found from the interviews that standstill detection systems are focussed on traffic scenarios where blockades greatly influence the traffic, e.g. segments without hard shoulders. For this study, the focus is on: bridges, tunnels, and hard shoulder running lanes.

To analyse the effects of the various systems, various indicators on traffic safety and flow are selected and analysed. The indicators are analysed in the microsimulation model VISSIM combined with a, Matlab controlled, COM interface. Through the COM interface dynamic processes occurring at incident locations are incorporated in the model, which include: dynamic speed limits, increased headway choice, and lane closures.

The microsimulation model is used to evaluate the differences between point and zone detectors. The two detection methods are evaluated on the following indicators: detection times, undetected and unwarned vehicles, maximum queue length, queue growth speed, discharge rates, delay, Time to Collision (TTC), Time integrated TTC (TIT), and deceleration rates.

It is not possible to evaluate all the distilled criteria in a simulation model, these criteria include: costs, traffic data accuracy, data accuracy, and ease of installation and maintenance. To evaluate these criteria, a decision flow chart has been and applied to the currently off-the-shelve available detector systems: inductive loops, passive and active infrared, radar, and Video Image Processing systems (VIP). The data used to evaluate the systems on the criteria is found from: suppliers, literature, and interviews. The scores of the chosen systems can be found in chapter 6.

At high flow, the selection of the type of detection system does not significantly affect the macroscopic indicators; queue length, queue growth, delay and discharge rates. This is partly due to the small share the detection times have on the total incident period, which is at most a difference of 40 seconds on 1500 seconds) and the fact that there is a handling time of 60 seconds.

The researched impact difference between point and zone detection systems on traffic safety does not give conclusive answers, this again due to the high variation in the simulated results and the lack of significant differences between the systems at high flow rates.

Although the microsimulation model does not give the desired results due to high variations, several useful insights have been found in regards to the impact difference between point and zone detection systems. It is proven that the difference between zone and point detection systems increases as the flow decreases, and that this does not go linearly when comparing different spacing distances between the point detection systems.

Analysing the systems on their characteristics and cost did give a more conclusive overview of the differences between the systems. By calculating the required detector points over a fiction freeway section of 500 meters it showed that the costs associated per unit of length are heavily influenced by the detection area of the system and the lifespan of the systems. This led to a comparison of the equivalent annual costs showing there is a very significant difference in costs between the point and zone detection systems. The results indicate that: VIP systems have the lowest EAC, Radar and Inductive Loops do not differ significantly from each other in EAC, and that active infrared systems have the highest EAC.

By combining the results of the model and the characteristics, it shows that the relation between cost and functionality is non-linear for point detector systems. By placing double the amount of detection points; effectively doubling the costs, the systems' detection times are not automatically halved. The relation is determined by the I/C ratio present when the incident occurs.

When analysing the various detection systems, the VIP detection systems have the potential to be the best cost-functionality ratio due to the system's ability to gather traffic data and its detection range. However, the VIP systems have an inherent weakness of being vulnerable to weather conditions. The low cost-functionality ratio is furthermore due to the lower equivalent annual cost compared to point detection systems. This lower equivalent annual cost is due to the higher range of detection, meaning fewer detectors are needed per length of freeway. Because the VIP systems' inherent weakness to external influences, they are the best solution in a closed environment, i.e. tunnels. An overview of the functionality of the various systems per traffic scenario is displayed in the score sheets in chapter 6.

8

Recommendations

8.1 Recommendations for Future Research

The results in chapter 5 are deemed inadequate to give a concrete comparison of the detection systems. This chapter gives an insight into the factors that influenced the results and how these can be addressed or improved in future research simulation incidents and detection systems.

Flow Rates

The first and most simple adaptation which can be implemented is the chosen I/C ratio. As described in this research the decision was made to simulate I/C ratios: 0.7, 0.8 and 0.9. This was decided due to the lack of detection by the larger spacing between detection points. The high levels of chosen flows however lead to small differences between the detection systems and suggest the differences between zone and point detection is relatively nugatory when looking at the macroscopic indicators. However the results show that the detection times, and thus the overall impacts, decrease with higher flows. Furthermore it is suggested that the higher the flow, the less room there is for overtaking; this would mean that with lower flows vehicles can pass the incident with greater ease, meaning the queue upstream of the incident grows at a higher pace than the decrease in flow.

Vehicle Behaviour

In the used model for this thesis there was no clear data available for the behaviour vehicles have, surrounding the first few seconds after the incident. To still be able to simulate the incident conditions certain assumptions were made. The first assumption made is that the vehicles approaching the incident during the first 5 seconds of the incident are not able to react adequately to the incident. This means that for the first 5 seconds vehicles will simply queue behind the incident. After these initial 5 seconds the vehicles receive the order to change lane. This means that the chosen time directly influences the detection times of the systems. To determine the correct value a study can be performed by simulating incidents in a car simulator and analysing the behaviour of real life drivers. For this research this is not done as it was outside of the scope of possibilities currently at hand.

Another subject that needs further investigation is the distance from which drivers know they will have to lane switch due to the impending incident vehicle. Currently the approaching vehicles

receive the command from up to 250 meters in front of the incident. This distance was chosen as it complied with the maximum look-ahead distance standardly used in VISSIM. This assumption however can possibly influence the detection times of the system.

To test the influence of the set 250 meters distance, a quick simulation is run in which the distance is set at 100 meters. Although the difference in the distance did change the results, the changes were not noticeable on all the runs. As expected the zone detection times did not alter, but the 25 and 50m systems did not show significant differences at the highest flows. The biggest differences were found in the 100m point detector. This means however that at lower flows the chosen distance can have an influence on the results.

Calibration

The model used in the research is calibrated on four parameters and calibrated to the maximum discharge rate. Although it was not possible to calibrate the model more accurately at the time for this research, in hindsight this choice might have greatly influenced the legitimacy of the results; the safety aspects are directly linked to the other parameters such as decelerations and accelerations of the modelled vehicles. Combining this with the above described vehicle comes to the inherent problem of this research, although the microsimulation program can be used it is dependent on the input given by the user requiring an extensive knowledge of vehicle behaviour surrounding incidents, which is absent at this time.

More recommendations are:

- Prices for the various detection systems should be updated to modern standards, this however may be difficult due to supplier's resistance to give price quotes.
- In this thesis only homogeneous systems have been tested, i.e. one type of system. Using multiple systems might lead to synergy effects.

8.2 Recommendations for Practise

Although the results do not give significant and concrete conclusions, the thesis has given important insights useful for the practice.

Asymmetric Detectors

In the above paragraph the recommendation is made to investigate the vehicle behaviour as it determines the rate vehicles will overtake the incident. Dutch freeway users are used to overtaking on the left; this is also simulated in the model. Furthermore, it is assumed the incident vehicles will naturally try to move to the rightmost lane. When an incident occurs on the leftmost lane, vehicles are forced to overtake on the right. Vehicle drivers are not used to this and probably will overtake slower, meaning the queue behind the incident will grow faster. This gives the possibility to suggest an asymmetric detector layout in which the distance between detector loops is increased for the left lane.

Larger Detector Distance at Hard Shoulder Running Lanes

A higher I/C ratio decreases the differences between the various detector systems. When considering that hard shoulder running lanes are only opened during peak hours, it can be

suggested that these lanes require a lower detector density than the other two scenarios: tunnels and bridges.

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Appendix A: Model Results

Detection Times

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	0.05	0	0.22	0	0	0	0.1	0	0.31
Point det. 25m	12.9	7	21.14	4.15	4	1.76	3.9	4	2.22
Point det. 50m	22.25	8	25.56	8.5	7	5.92	6.1	5	2.69
Point det. 100m	37.9	29.5	20.75	24.5	23	10.07	17.95	18	10.20
MTM	35.3	30.5	13.81	27.35	29	8.60	25.4	26.5	9.47
							Incident location = 100m		

Table 32: System Time (s) per Detection system, incident location=100m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	0	0	0.89	0.1	0	0.31	0.1	0	0.31
Point det. 25m	14.6	9	18.48	6.1	5.5	3.23	5.6	5	3.35
Point det. 50m	20.3	12	18.20	9.8	8.5	5.64	8.8	8	5.59
Point det. 100m	39.8	34	14.38	23	22.5	11.06	21.7	20	9.81
MTM	129.1	123.5	31.47	89.3	87	15.16	76.0	76.5	8.80
							Incident location = 300m		

Table 33: System Time (s) per Detection system, incident location=300m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	0	0	0.72	0	0	0.89	0	0	0.22
Point det. 25m	12	6	18.84	7	5	8.44	5	5	2.97
Point det. 50m	17	11	14.68	15	10	12.99	10	9	6.28
Point det. 100m	41	34	28.35	34	34	7.52	27	28	8.66
MTM	213	212	40.20	157	157	19.03	126	124	10.10
							Incident location = 500m		

Table 34: System Time (s) per Detection system, incident location=500m

Undetected Vehicles

For the undetected vehicles per incident location and I/C ratio the results are displayed in the tables below.

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**
Zone det.	0	0	0	0	0	0	1	0	4
Point det. 25m	18	12	23	12	12	0	11	12	3
Point det. 50m	30	13	29	15	12	7	13	12	2
Point det. 100m	51	46	24	37	34	15	29	28	16
MTM	47	44	14	38	39	12	39	39	15
							Incident location = 100m		

Table 35: Number of Undetected Vehicles per System, incident location = 100m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**
Zone det.	1	0	3	0	0	0	1	0	3
Point det. 25m	21	12	22	13	12	1	13	12	2
Point det. 50m	27	15	22	16	12	7	16	13	7
Point det. 100m	53	53	17	36	35	16	36	33	17
MTM	178	168	33	140	138	18	128	124	15
							Incident location = 300m		

Table 36: Number of Undetected Vehicles per System, incident location = 300m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**	**Mean**	**Median**	**std.**
Zone det.	2	0	4	1	0	3	1	0	3
Point det. 25m	19	12	21	14	12	8	12	12	0
Point det. 50m	23	14	17	21	15	16	17	15	8
Point det. 100m	54	45	32	50	50	12	44	47	14
MTM	297	296	40	244	245	22	216	212	16
							Incident location = 500m		

Table 37: Number of Undetected Vehicles per System, incident location = 500m

Unwarned Vehicles

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	75	77	6	77	77	6	76	76	6
Point det. 25m	89	85	25	81	80	7	78	78	7
Point det. 50m	99	88	29	85	83	9	80	79	7
Point det. 100m	114	107	25	98	96	13	90	90	14
MTM	110	107	18	99	98	10	97	98	14
							Incident location = 100m		

Table 38: Number of Unwarned Vehicles per System, incident location = 100m

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	86	83	11	97	98	7	103	102	3
Point det. 25m	105	95	29	106	107	9	112	110	7
Point det. 50m	114	103	26	111	112	12	117	115	9
Point det. 100m	138	139	23	131	131	19	135	133	16
MTM	239	229	34	195	192	18	181	177	14
							Incident location = 300m		

Table 39: Number of Unwarned Vehicles per System, incident location = 300m

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	86	84	11	98	98	8	104	104	3
Point det. 25m	102	97	27	109	104	15	113	114	7
Point det. 50m	107	103	22	122	115	21	123	119	11
Point det. 100m	140	133	35	152	152	14	152	153	16
MTM	358	353	40	301	304	18	271	268	13
							Incident location = 500m		

Table 40: Number of Unwarned Vehicles per System, incident location = 500m

Queue Length

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	4029	4027	174	5535	5500	268	7373	7418	301
Point det. 25m	4049	4024	220	5596	5571	242	7358	7339	355
Point det. 50m	4039	4051	231	5596	5626	235	7382	7411	293
Point det. 100m	4115	4113	217	5690	5781	256	7380	7341	280
MTM	4153	4160	180	5784	5764	259	7499	7565	267
							Incident location = 100m		

Table 41: Maximum Queue Length (m) per System, incident location =100m

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	4533	4595	214	6155	6174	266	7886	7948	261
Point det. 25m	4617	4576	193	6149	6127	304	7923	7946	292
Point det. 50m	4623	4698	208	6202	6195	287	7959	8043	287
Point det. 100m	4623	4675	247	6230	6196	257	7981	7958	287
MTM	4795	4775	198	6451	6512	265	8138	8131	292
							Incident location = 300m		

Table 42: Maximum Queue Length (m) per System, incident location =300m

System	I/C Ratio 0.7 Mean	Median	std.	I/C Ratio 0.8 Mean	Median	std.	I/C Ratio 0.9 Mean	Median	std.
Zone det.	4080	4091	222	5580	5579	234	7384	7356	296
Point det. 25m	4116	4163	246	5630	5565	282	7382	7375	291
Point det. 50m	4117	4171	187	5644	5611	230	7400	7382	314
Point det. 100m	4166	4214	203	5731	5793	250	7441	7436	319
MTM	4487	4479	180	6100	6092	257	7810	7825	268
							Incident location = 500m		

Table 43: Maximum Queue Length (m) per System, incident location =500m

Queue Growth

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**
Zone det.	78	115	275	61	91	195	49	82	158
Point det. 25m	79	116	254	61	90	197	49	81	164
Point det. 50m	79	125	247	61	95	200	49	80	159
Point det. 100m	95	132	286	61	100	203	49	86	165
MTM	98	132	292	55	102	193	49	88	167
							Incident location = 100m		

Table 44: Queue growth (s), incident location = 100m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**
Zone det.	77	109	133	53	86	109	44	74	91
Point det. 25m	77	119	140	53	84	111	44	76	95
Point det. 50m	79	117	139	53	89	110	44	78	94
Point det. 100m	84	124	151	53	95	115	44	82	99
MTM	84	142	186	53	99	137	44	85	111
							Incident location = 300m		

Table 45: Queue growth (s), incident location = 300m

	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
System	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**	**300m**	**500m**	**1000m**
Zone det.	105	157	190	87	128	161	74	113	128
Point det. 25m	109	156	195	87	130	157	75	112	132
Point det. 50m	111	157	194	89	113	166	76	116	137
Point det. 100m	117	166	204	97	137	176	78	118	142
MTM	136	239	304	97	165	233	78	134	184
							Incident location = 500m		

Table 46 *: Queue growth (s), incident location = 500m*

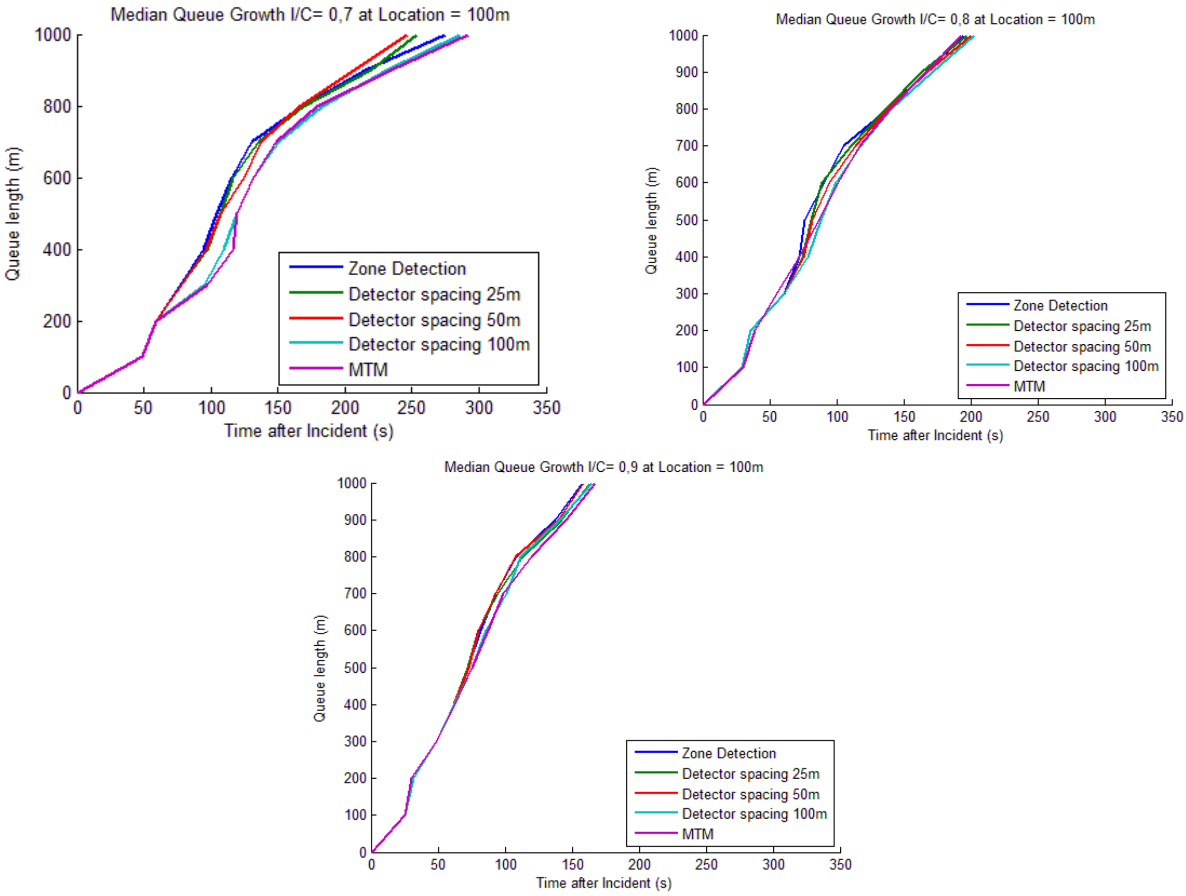

Figure 27: Queue growth, incident location = 100m.

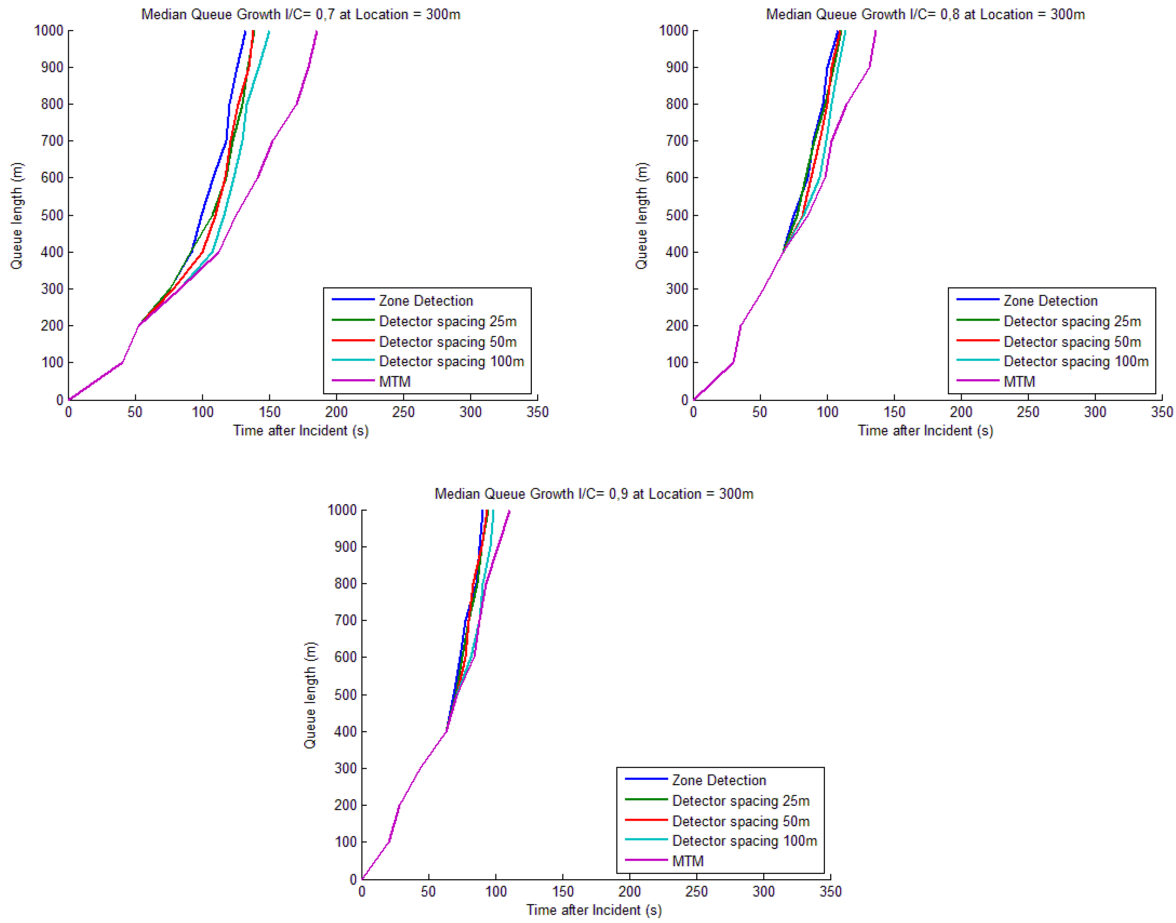

Figure 28: Queue growth, incident location = 300m

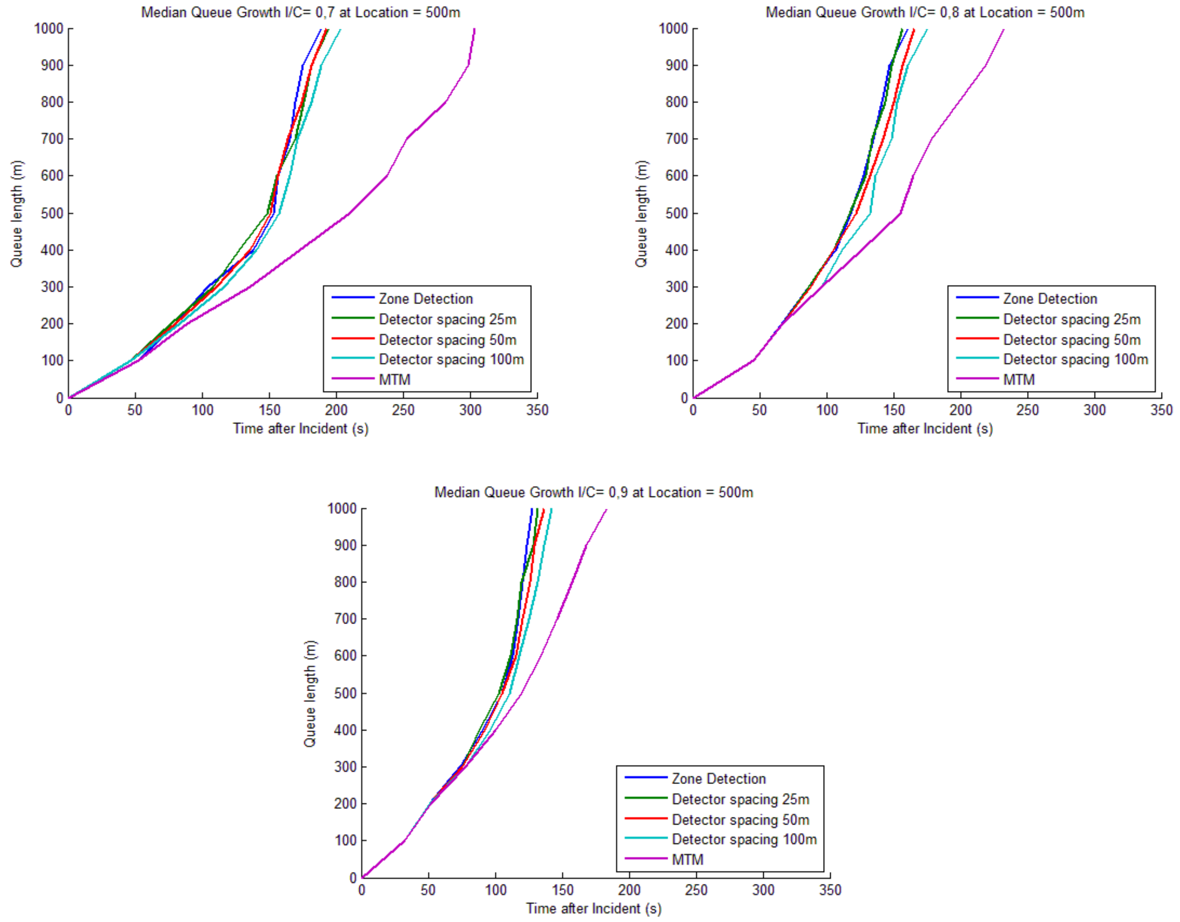

Figure 29: Queue growth, incident location = 500m

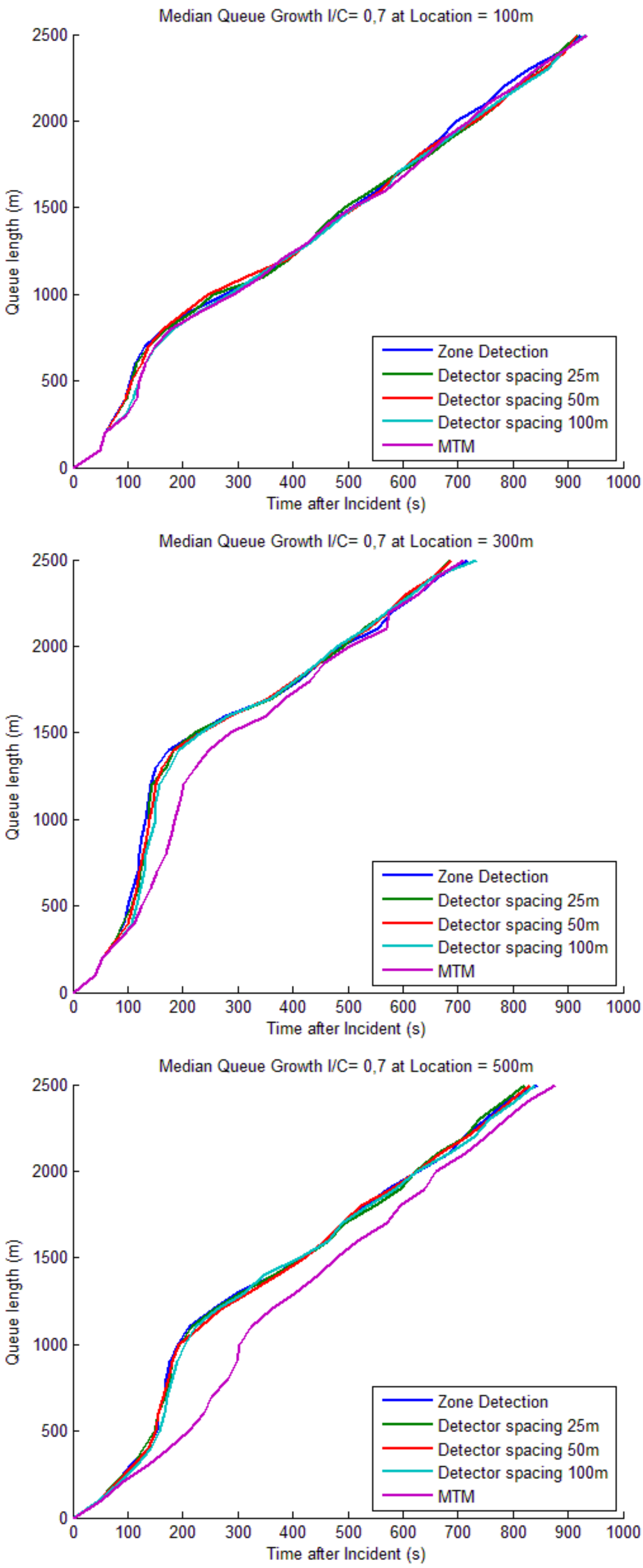

Figure 30: Queue Growth, I/C = 0.7

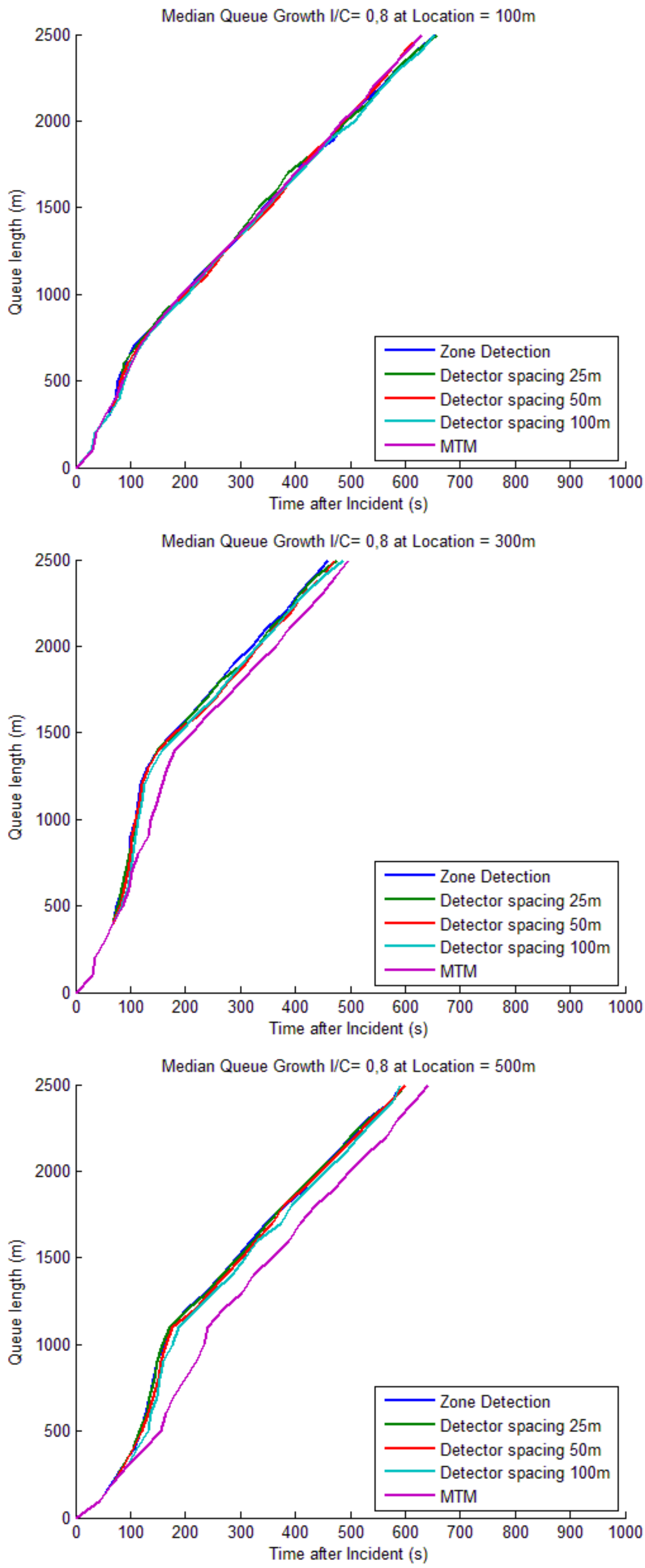

Figure 31: Queue Growth, I/C=0.8

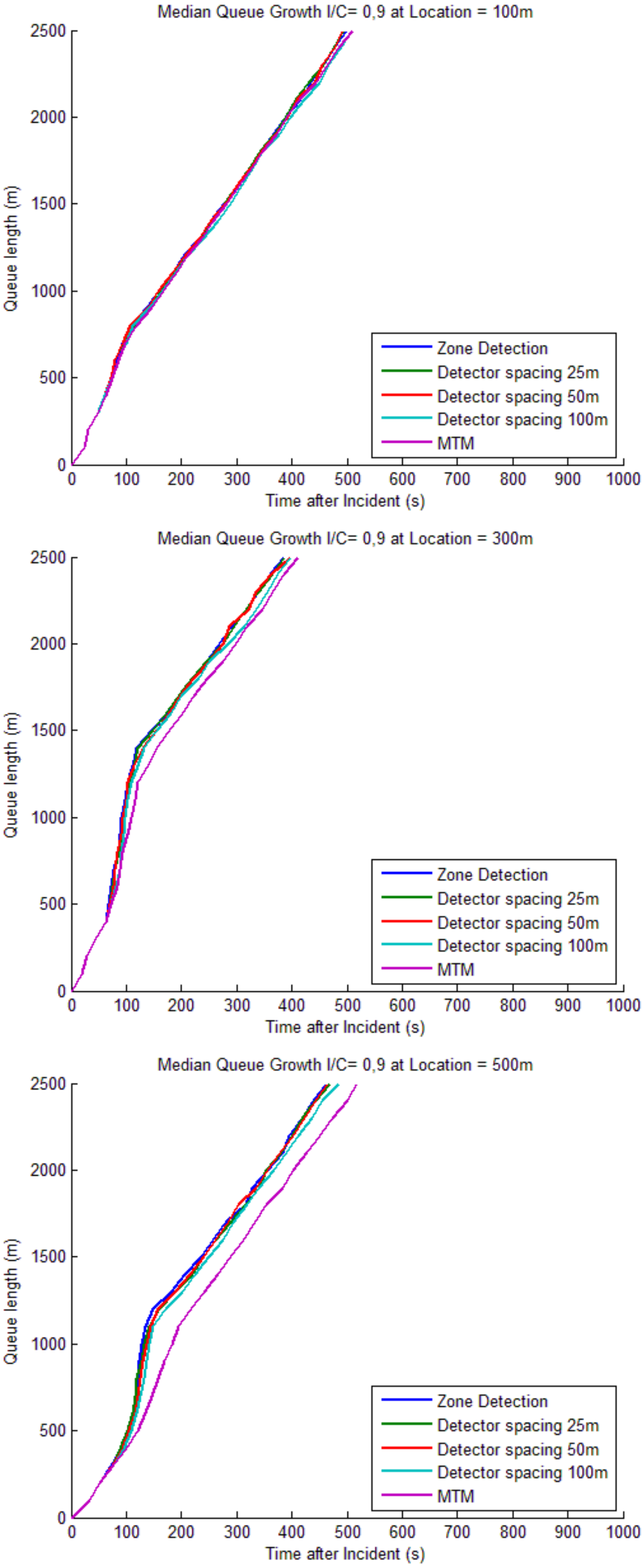

Figure 32: Queue Growth, I/C = 0.9

Discharge Rates

System	I/C Ratio 0.7				I/C Ratio 0.8				I/C Ratio 0.9			
	Period 2		Period 3		Period 2		Period 3		Period 2		Period 3	
	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	std.
Zone det.	3840	404	2940	298	3900	334	2940	256	3930	322	2820	228
Point 25m	3749	346	2979	254	3853	319	2935	282	3911	297	2937	271
Point 50m	3736	359	2936	252	3832	292	2955	253	3867	315	2965	242
Point 100m	3623	317	3158	170	3686	241	3060	187	3765	203	3089	173
MTM	3599	312	3171	166	3645	187	3078	160	3692	192	3148	155
									Incident location = 100m			

Table 47: Discharge (veh/h) per System, incident location=100m

System	I/C Ratio 0.7				I/C Ratio 0.8				I/C Ratio 0.9			
	Period 2		Period 3		Period 2		Period 3		Period 2		Period 3	
	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	std.
Zone det.	3750	327	3030	277	3660	272	2940	225	3600	337	3065	294
Point 25m	3700	238	3204	278	3626	247	3093	264	3600	313	3086	277
Point 50m	3600	245	3137	261	3625	247	3137	172	3548	307	3212	268
Point 100m	3541	201	3265	145	3558	166	3269	247	3509	204	3222	281
MTM	3425	138	3279	47	3392	109	3294	99	3396	144	3301	114
									Incident location = 300m			

Table 48: Discharge (veh/h) per System, incident location=300m

System	I/C Ratio 0.7				I/C Ratio 0.8				I/C Ratio 0.9			
	Period 2		Period 3		Period 2		Period 3		Period 2		Period 3	
	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	Std.	Median	std.
Zone det.	3927	402	3360	163	3960	311	3330	163	4020	303	3360	162
Point 25m	3823	287	3337	166	3871	308	3315	73	3915	274	3314	143
Point 50m	3802	287	3345	184	3807	257	3368	113	3880	267	3298	130
Point 100m	3729	179	3311	58	3733	173	3394	116	3830	179	3370	219
MTM	3506	91	3289	33	3563	93	3327	33	3600	95	3356	56
									Incident location = 500m			

Table 49: Discharge (veh/h) per System, incident location=500m

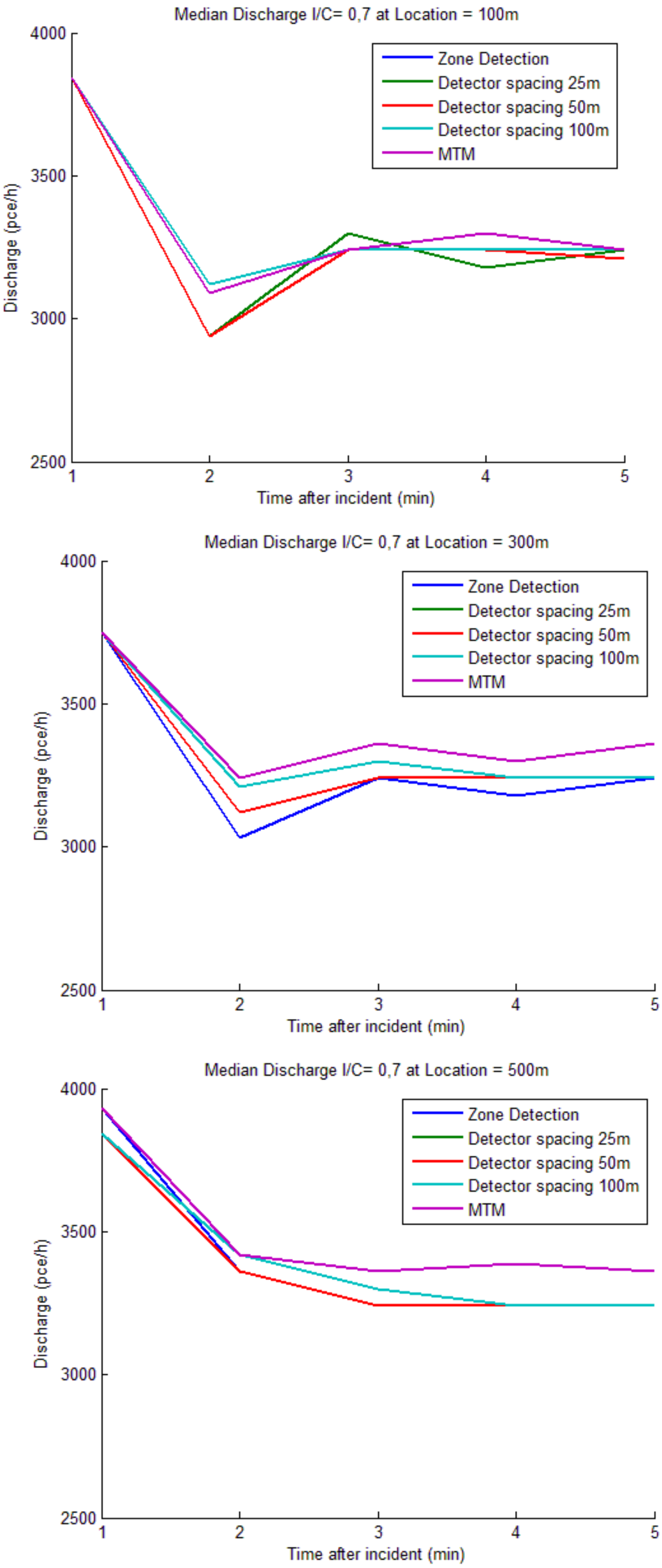

Figure 33: Discharge I/C Ratio 0.7

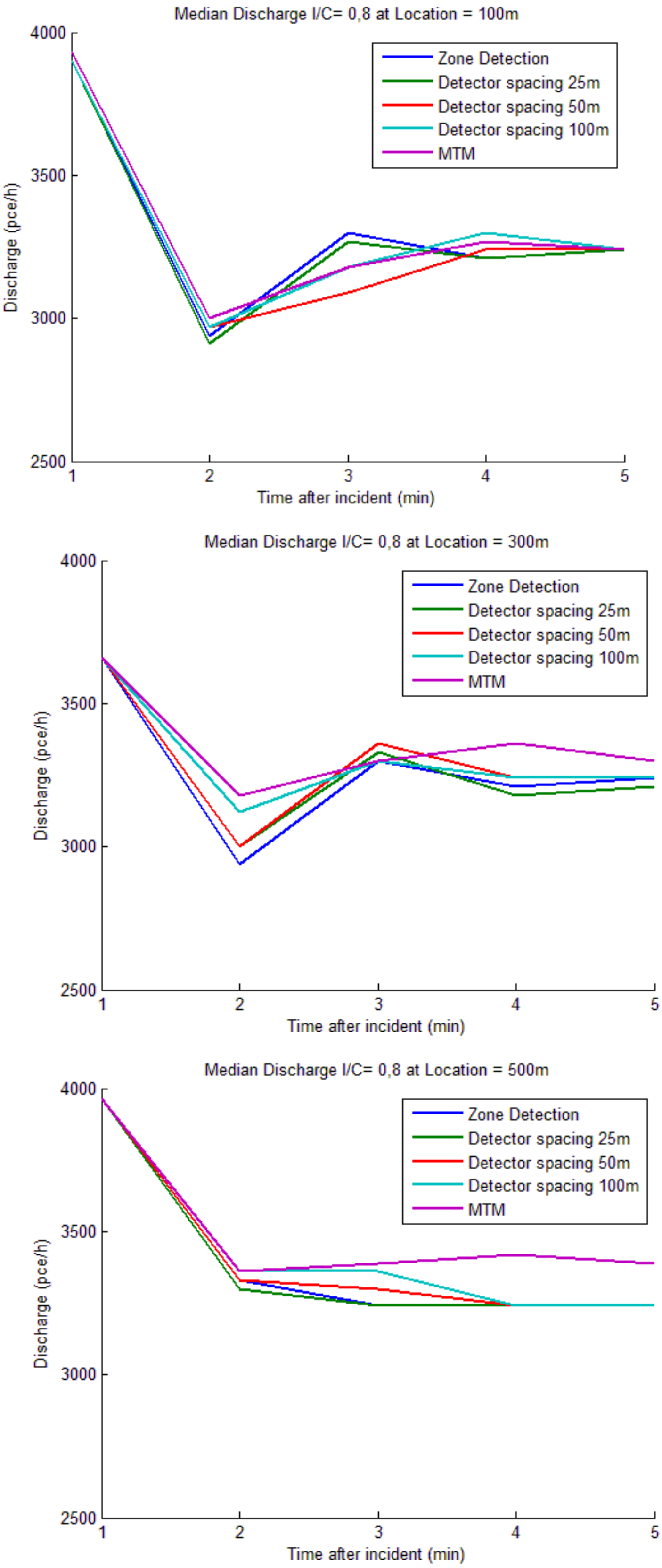

Figure 34: Discharge I/C Ratio 0.8

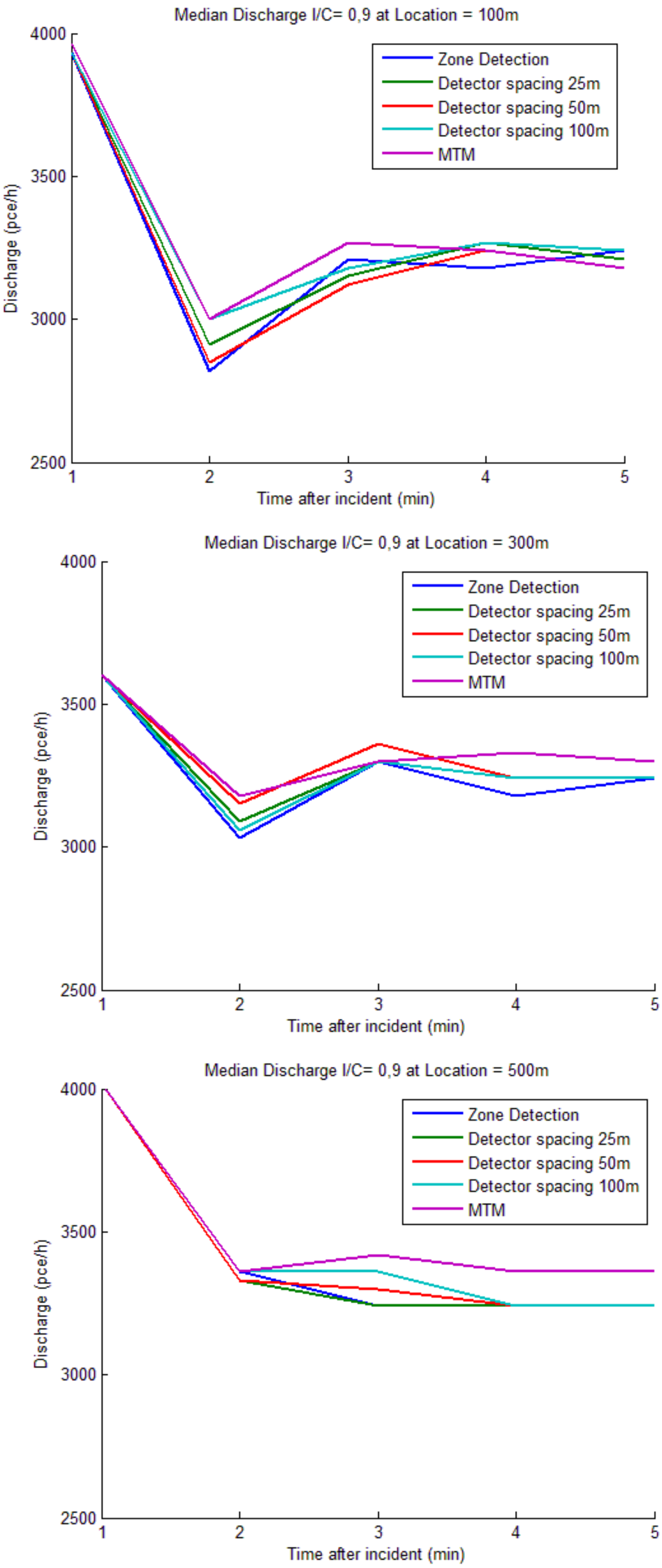

Figure 35: Discharge I/C Ratio 0.9

Delay Times

System	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	330.5	327.1	25.6	544.0	535.9	33.9	783.0	784.7	48.3
Point det. 25m	333.7	335.6	26.1	546.9	539.5	32.8	784.8	786.2	49.3
Point det. 50m	334.8	337.7	28.0	547.3	544.2	33.5	785.2	781.2	47.9
Point det. 100m	341.6	346.9	26.4	554.3	555.5	36.2	791.0	790.5	45.9
MTM	341.7	344.7	26.3	589.1	588.0	34.9	794.0	792.3	46.5
							Incident location = 100m		

Table 50: Total Delay Time (h) , incident location = 100m

System	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	321.6	323.0	25.8	541.1	537.5	36.3	775.0	770.2	47.8
Point det. 25m	329.7	334.7	26.3	541.0	535.6	34.7	770.0	776.9	49.0
Point det. 50m	330.3	335.5	27.1	541.7	536.7	37.1	775.7	777.4	49.9
Point det. 100m	334.7	332.4	27.5	547.7	543.3	34.4	782.0	780.9	49.9
MTM	356.2	355.0	24.0	569.4	570.1	34.2	804.9	802.9	50.7
							Incident location = 300m		

Table 51: Total Delay Time (h) , incident location = 300m

System	I/C Ratio 0.7			I/C Ratio 0.8			I/C Ratio 0.9		
	Mean	Median	std.	Mean	Median	std.	Mean	Median	std.
Zone det.	317.2	322.1	24.4	525.6	525.7	33.7	759.3	754.0	45.5
Point det. 25m	321.2	324.3	26.8	526.3	523.8	35.0	759.7	758.0	45.6
Point det. 50m	321.8	327.6	26.2	529.8	529.8	33.5	763.2	761.1	48.1
Point det. 100m	326.0	328.6	26.2	535.3	536.5	34.3	771.5	760.6	50.1
MTM	368.8	372.9	24.0	574.1	569.4	31.2	810.2	808.5	47.9
							Incident location = 500m		

Table 52: Total Delay Time (h) , incident location = 500m

Time to Collision

I/C Ratio	% TTC < 4 s Median	Std	Absolute Median	Std
0.7	4.21	1,25	552	244
0.8	5,25	1,13	691	209
0.9	6,04	1,25	917	234

Table 53: Null measurements TTC (s) for incident location = 100m

With the null measurement known the data received from the measurement period is introduced. Comparing the results of the various detection systems should give the nett increase in TTC values per detection system. The results are shown in Table 54.

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	13.04	1,91	8.83	2087	443	1535
Point det. 25m	12.84	1.72	8.63	2151	423	1599
Point det. 50m	12.79	1.79	8.58	2177	412	1625
Point det. 100m	13.51	1.78	9.30	2248	417	1696
MTM	13.53	1.78	9.32	2240	421	1688
				I/C ratio = 0.7		

Table 54: Time to Collision, incident location = 100m, I/C ratio = 0.7

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	13.04	1.03	7.79	2140	186	1449
Point det. 25m	13.43	0.87	8.18	2136	182	1445
Point det. 50m	13.23	0.81	7.98	2139	14	1448
Point det. 100m	13.57	0.77	8.32	2188	150	1497
MTM	13.55	1.01	8.29	2229	106	1538
				I/C ratio = 0.8		

Table 55: Time to Collision, incident location = 100m, I/C ratio = 0.8

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	13.13	0.94	7.09	2253	138	1336
Point det. 25m	12.92	1.06	6.88	2215	155	1298
Point det. 50m	13.06	1.03	7.02	2252	154	1335
Point det. 100m	13.24	0.91	7.20	2242	134	1325
MTM	13.36	0.81	7.32	2302	133	1385
				I/C ratio = 0.9		

Table 56: Time to Collision, incident location = 100m, I/C ratio = 0.9

I/C Ratio	% TTC < 4 s Median	Std	Absolute Median	Std
0.7	7.68	2.13	1808	653
0.8	11.35	1.65	2590	490
0.9	12.89	2.27	2871	694

Table 57: Null measurements TTC (s) for incident location = 300m

In the null measurement an increase is found, this is expected as the measurement period and size of the measurement area is increased for this incident location. When applying the null measurement to the data found for the various detection systems the following tables can be produced.

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	15.02	0.89	7.34	6290	745	4482
Point det. 25m	14.52	1.19	6.84	6537	752	4729
Point det. 50m	14.40	0.92	6.72	6625	741	4817
Point det. 100m	13.94	0.84	6.26	6628	820	4820
MTM	12.54	0.54	4.86	6997	1024	5189
				I/C ratio = 0.7		

Table 58: Time to Collision, incident location = 300m, I/C ratio = 0.7

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	13.64	0.63	2.29	5707	407	3117
Point det. 25m	13.35	0.64	2.00	5684	458	3094
Point det. 50m	13.31	0.45	1.96	5715	432	3125
Point det. 100m	12.85	0.64	1.50	5760	520	3170
MTM	12.14	0.52	0.79	5956	477	3366
				I/C ratio = 0.8		

Table 59: Time to Collision, incident location = 300m, I/C ratio = 0.8

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	13.16	1.02	0.27	5568	385	2697
Point det. 25m	12.87	0.78	-0.02	5620	402	2749
Point det. 50m	12.90	0.88	0.01	5562	365	2691
Point det. 100m	12.24	1.09	-0.65	5542	448	2671
MTM	11.79	0.60	-1.1	5612	333	2741
				I/C ratio = 0.9		

Table 60: Time to Collision, incident location = 300m, I/C ratio = 0.9

For the incident location = 500m, the following null measurements have been found, these are displayed in Table 61.

I/C Ratio	% TTC < 4 s Median	Std	Absolute Median	Std
0.7	0.02	0.04	6	13
0.8	0.03	0.02	10	8
0.9	0.04	0.05	13	17

Table 61: Null measurements TTC (s) for incident location = 500m

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	0.94	0.17	0.92	725	149	719
Point det. 25m	1.01	0.22	0.99	853	206	847
Point det. 50m	1.04	0.20	1.02	869	207	863
Point det. 100m	1.13	0.18	1.11	922	135	916
MTM	1.58	0.22	1.56	1724	182	1718
				I/C ratio = 0.7		

Table 62: Time to Collision, incident location = 500m, I/C ratio = 0.7

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	0.79	0.11	0.76	578	76	568
Point det. 25m	0.93	0.13	0.90	647	92	637
Point det. 50m	0.91	0.14	0.88	659	95	659
Point det. 100m	1.03	0.13	1.00	807	94	797
MTM	1.34	0.11	1.31	1287	86	1277
				I/C ratio = 0.8		

Table 63: Time to Collision, incident location = 500m, I/C ratio = 0.8

Detection System	% TTC < 4 s Median	Std	Nett	Absolute Median	Std	nett
Zone det.	0.83	0.10	0.79	571	79	558
Point det. 25m	0.90	0.09	0.86	633	70	620
Point det. 50m	0.89	0.08	0.85	633	60	620
Point det. 100m	0.94	0.12	0.94	727	99	714
MTM	1.34	0.10	1.30	1040	94	1027
				I/C ratio = 0.9		

Table 64: Time to Collision, incident location = 500m, I/C ratio = 0.9

Time Integrated TTC

For the incident location =100m the following null measurements have been found.

I/C Ratio	TIT < 4s Median	Std
0.7	258	114
0.8	307	111
0.9	412	111

Table 65: Null measurements TIT (s) for incident location = 100m

When applying the null measurements into the results from the incident location, the following tables can be created.

Detection System	TIT < 4s Median	Std	Nett
Zone det.	1244	303	986
Point det. 25m	1248	289	990
Point det. 50m	1262	275	1004
Point det. 100m	1360	282	1102
MTM	1359	287	1101
			I/C ratio = 0.7

Table 66: TIT, incident location = 100m, I/C ratio = 0.7

Detection System	TIT < 4s Median	Std	Nett
Zone det.	1321	120	1014
Point det. 25m	1329	121	1022
Point det. 50m	1310	103	1003
Point det. 100m	1350	101	1043
MTM	1378	79	1071
			I/C ratio = 0.8

Table 67: TIT, incident location = 100m, I/C ratio = 0.8

Detection System	TIT < 4s Median	Std	Nett
Zone det.	1385	83	973
Point det. 25m	1378	94	966
Point det. 50m	1403	102	991
Point det. 100m	1401	84	989
MTM	1431	90	1019
			I/C ratio = 0.9

Table 68: TIT, incident location = 100m, I/C ratio = 0.9

For the incident location =300m the following null measurements have been found.

I/C Ratio	TIT < 4s Median	Std
0.7	796	347
0.8	1230	241
0.9	1372	378

Table 69: Null measurements TIT (s) for incident location = 300m

When applying the null measurements into the results from the incident location, the following table can be created.

Detection System	TIT < 4s Median	Std	Nett
Zone det.	3818	536	3022
Point det. 25m	3931	558	3135
Point det. 50m	3951	552	3155
Point det. 100m	3897	621	3101
MTM	4095	835	3299
			I/C ratio = 0.7

Table 70: TIT, incident location = 300m, I/C ratio = 0.7

Detection System	TIT < 4s Median	Std	Nett
Zone det.	3524	291	2294
Point det. 25m	3476	337	2246
Point det. 50m	3547	321	2317
Point det. 100m	3500	397	2270
MTM	3573	386	2343
			I/C ratio = 0.8

Table 71: TIT, incident location = 300m, I/C ratio = 0.8

Detection System	TIT < 4s Median	Std	Nett
Zone det.	3429	269	2057
Point det. 25m	3413	297	2183
Point det. 50m	3396	253	2166
Point det. 100m	3348	323	2118
MTM	3458	247	2228
			I/C ratio = 0.9

Table 72: TIT, incident location = 300m, I/C ratio = 0.9

For the incident location =500m the following null measurements have been found.

I/C Ratio	TIT < 4s Median	Std
0.7	1	4
0.8	2	2
0.9	2	4

Table 73: Null measurements TIT (s) for incident location = 500m

When applying the null measurements to the simulated incident TIT values the following tables can be created.

Detection System	TIT < 4s Median	Std	Nett
Zone det.	245	30	244
Point det. 25m	273	50	272
Point det. 50m	272	49	271
Point det. 100m	278	35	277
MTM	432	69	431
			I/C ratio = 0.7

Table 74: TIT, incident location = 500m, I/C ratio = 0.7

Detection System	TIT < 4s Median	Std	Nett
Zone det.	209	19	207
Point det. 25m	221	21	219
Point det. 50m	230	16	228
Point det. 100m	250	20	248
MTM	376	36	375
			I/C ratio = 0.8

Table 75: TIT, incident location = 500m, I/C ratio = 0.8

Detection System	TIT < 4s Median	Std	Nett
Zone det.	201	21	199
Point det. 25m	211	23	209
Point det. 50m	209	16	207
Point det. 100m	239	31	237
MTM	348	37	346
			I/C ratio = 0.9

Table 76: TIT, incident location = 500m, I/C ratio = 0.9

Deceleration

Incident location =100m

For the incident location =100m the following null measurements have been found.

I/C Ratio	% A < -4 m/s^2 Median	Std	Absolute Median	Std
0.7	0.00	0.15	0	4
0.8	0.00	0.18	0	6
0.9	0.00	0.26	0	9

Table 77: Null measurement deceleration, incident location = 100m

At first glance the null measurements for the deceleration rates seem to be a better aspect to compare with as the results show a low rate of occurrence. This is only the case however if the measurements from the incident location differ from the above results. Applying the null measurements to the incident results, give the following results.

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.85	0.93	129	49	129
Point det. 25m	1.78	0.81	131	49	131
Point det. 50m	1.85	0.84	131	48	131
Point det. 100m	1.87	0.81	127	48	127
MTM	1.87	0.81	127	48	127
				I/C ratio = 0.7	

Table 78: Deceleration, incident location = 100 m, I/C = 0.7

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.52	1.58	124	129	124
Point det. 25m	1.51	1.55	124	131	124
Point det. 50m	1.44	1.52	121	128	121
Point det. 100m	1.47	1.58	117	132	117
MTM	1.23	0.42	106	33	106
				I/C ratio = 0.8	

Table 79: Deceleration, incident location = 100 m, I/C = 0.8

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.25	0.79	118	68	118
Point det. 25m	1.37	0.70	125	62	125
Point det. 50m	1.41	0.68	131	61	131
Point det. 100m	1.29	0.72	117	63	117
MTM	1.32	0.72	118	62	118
				I/C ratio = 0.9	

Table 80: Deceleration, incident location = 100 m, I/C = 0.9

Incident location =300m

Unlike the previous safety aspect, the percentage of decelerations above the threshold seems to increase with the increased null measurement time and section length; however the found null measurement results are still close to zero, at first glance suggesting a normal traffic flow.

I/C Ratio	% A < -4 m/s^2 Median	Std	Absolute Median	Std
0.7	0.08	0.06	12	8
0.8	0.09	0.07	12	10
0.9	0.09	0.16	12	23

Table 81: Null measurement deceleration, incident location = 300m

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.62	0.33	533	118	522
Point det. 25m	1.72	0.42	602	106	590
Point det. 50m	1.73	0.47	616	95	604
Point det. 100m	1.71	0.43	665	80	653
MTM	1.58	0.39	694	87	682
				I/C ratio = 0.7	

Table 82: Deceleration, incident location = 300 m, I/C = 0.7

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.58	0.34	549	142	537
Point det. 25m	1.48	0.30	531	118	519
Point det. 50m	1.48	0.34	549	128	537
Point det. 100m	1.57	0.68	610	144	598
MTM	1.36	0.28	594	121	582
				I/C ratio = 0.8	

Table 83: Deceleration, incident location = 300 m, I/C = 0.8

Detection System	% A < -4 m/s^2 Median	Std	Absolute Median	Std	nett
Zone det.	1.34	0.51	470	237	458
Point det. 25m	1.33	0.88	505	402	493
Point det. 50m	1.36	0.88	519	417	507
Point det. 100m	1.26	0.73	490	336	478
MTM	1.24	0.44	496	213	484
				I/C ratio = 0.9	

Table 84: Deceleration, incident location = 300 m, I/C = 0.9

Incident location =500m

I/C Ratio	% A < -4 m/s² Median	Std	Absolute Median	Std
0.7	0.03	0.05	12	17
0.8	0.04	0.04	12	14
0.9	0.06	0.08	20	26

Table 85: Null measurement deceleration, incident location = 500m

Detection System	% A < -4 m/s² Median	Std	Absolute Median	Std	nett
Zone det.	1.02	0.19	833	186	821
Point det. 25m	1.10	0.32	863	292	851
Point det. 50m	1.08	0.31	863	300	851
Point det. 100m	1.08	0.23	878	223	866
MTM	1.15	0.17	1253	211	1241
				I/C ratio = 0.7	

Table 86: Deceleration, incident location = 500 m, I/C = 0.7

Detection System	% A < -4 m/s² Median	Std	Absolute Median	Std	nett
Zone det.	1.09	0.17	751	141	739
Point det. 25m	1.04	0.16	756	138	744
Point det. 50m	1.10	0.20	796	149	784
Point det. 100m	1.20	0.29	961	239	749
MTM	1.10	0.21	1055	231	1043
				I/C ratio = 0.8	

Table 87: Deceleration, incident location = 500 m, I/C = 0.8

Detection System	% A < -4 m/s² Median	Std	Absolute Median	Std	nett
Zone det.	1.10	0.22	743	154	723
Point det. 25m	1.14	0.18	788	133	768
Point det. 50m	1.16	0.25	828	187	808
Point det. 100m	1.13	0.36	864	273	844
MTM	1.10	0.27	981	241	861
				I/C ratio = 0.9	

Table 88: Deceleration, incident location = 500 m, I/C = 0.9