Increasing speed limit compliance in motorway work zones

A human system integration approach

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bam infra

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by

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Preface

This research project was carried out to partially fulfil the requirements for the degree of Master of Science in Civil Engineering with the Integral Design Management annotation at the Delft University of Technology. The topic of this graduation thesis is increasing speed limit compliance in motorway work zones. The topic is internationally recognised in literature, but the subject is brought forward by BAM Infra. BAM Infra is a major Dutch construction-services business and part of the Royal BAM group. The report consists of 2 integrated topics, the human system integration design of the speed management measure and the evaluation of a field trial deploying this measure.

I would like to thank BAM Infra for giving me the opportunity to conduct this research. I am very grateful for being part of the Traffic Management team of BAM Infraconsult for the last nine months, I have enjoyed every single discussion on safety and traffic management issues with all team members. I would also like to thank Berend Brinkhuis for the inspirational safety knowledge meetings. My supervisors Frank Baelde and Johan Borsje were very supportive during the research and I would like to thank them for their critical reviews during the project.

Furthermore, I would like to thank everybody who contributed to the field trial. I would like to thank Rijkswaterstaat, road authority of the Netherlands, for their support in the design and deployment of the field trial. Maaikel Koenis for his time to discuss national guidelines and motorway policy. Especially within the district 'midden Nederland' (central Netherlands), I found support of the traffic data centre, traffic counter and traffic management centre, this was of vital essence. I would like to thank the team of Poort van Bunnik, especially Rino Lafranceschina and Harry van der Heijden, for their essential support, without their advise this research would not have been possible.

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Finally, I would like to thank my friends and family for supporting me throughout this busy period. First of all, my boyfriend Jorrit was able to keep me motivated during the more difficult periods. I'd like to thank my friend Lieke for her critical review and support during the research. My room mates from Julianalaan 13 and Lange Beestenmarkt 97 provided pleasant company after long days of work. Finally I want to thank my parents who supported me, not only during my final year, but during my entire study period.

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Summary

Speeding in motorway work zones lowers the perceived safety of road workers and increases the accident risks of traffic participants. In a work zone, traffic participants share the road with road workers. Road workers are often vulnerable and feel threatened by vehicles passing with high speed. The work zone design guidelines prescribe the use of traffic cones and lower speed limits to protect road workers. However, the road workers still feel unsafe. Traffic participants are also at risk since work zones are crash prone areas. Driving with high speeds in these areas also increases the severity of risky events. This study aims at designing and testing a new speed management measure for a typical overnight Dutch motorway work zone.

There are multiple causes for speeding. Unwillingness of drivers is an often named cause, but incompetence is mentioned in the literature as well. The driving task in work zones deviates from normal driving and this causes nuisance for drivers. Drivers have to slow down, which proves to be hard after driving at high speed for a long time. Another nuisance factor is that sometimes there is no visible activity in a work zone. In case of an empty work zone, drivers feel that their effort was meaningless. The driver's trust in the warnings, speed limit and other traffic measures of the work zone system, is damaged.

Currently internationally applied countermeasures often have short-term and low speed reduction effects. From police dummies to speed monitoring displays, these measures do not form a definitive solution to the problem. A proven effective solution is section control which is an automated enforcement method. Automated enforcement evokes societal resentment of 'intrusive government' and is therefore politically unfavourable. Recent research effort is put into the credibility of a speed limit. A high credibility of a speed limit would increase compliance since drivers have a natural tendency towards this speed limit.

To design a new solution for the problem, a design method is chosen which incorporates human behavioural factors and system engineering. This design method is called Human System Integration (HSI). The design method is function based, first the functions of the system are defined (i.e, what the system should do), and then the components to perform these functions are chosen. In this design, the functions are matched to the user needs, in this case drivers, workers and road operators.

The user needs are compared to the current system capabilities and capability gaps are identified. The current system is lacking flexibility and therefore the work zone and speed limit are sometimes interpreted as not credible. Also, some work phases are more dangerous than others and information about these phases may increase the awareness of the work zone with drivers. The designed solution aims to optimise the credibility of the total work zone system. Credibility is identified as a so-called 'non-functional requirement' of the work zone system and incorporated in the design. To optimise credibility, the work zone should meet the drivers' expectations. In this study a portable changeable message sign (PCMS) is added to the design to set driver expectations about the work zone. The possible displayed messages depending on the work zone phase are: 'Placement of traffic measures', 'No visible work activity', 'Work on crash barrier' and 'Removal of traffic measures'. Furthermore, if there is no visible work activity in the work zone, the speed limit is increased from 70 km/h to 90 km/h.

The design is tested on the A12 motorway in one work zone and compared to two different work zones on the A12. The test work zone is situated upstream of the initial measurements work zone on the same road stretch. For the evaluation, minute aggregated loop detector data is available of 10 detectors per work zone. A one on one comparison of the work zones is impossible due to large spatial and temporal differences. To incorporate these spatial and temporal factors like on-ramps and truck share a Multiple Linear Regression Model (MLRM) is estimated.

The PCMS has a small but significant effect of -1 km/h. The spatial impact of the PCMS is significant up till 2.7 km downstream of the sign location. The evaluation of the increased speed limit shows that speed limit compliance is higher during the 90 km/h speed limit in the 'no visible work activity' phase. The flow explains a speed decreases of 0.01 km/h per vehicles/lane/hour. The truck share measurements are added to the model using two vehicle length detectors in each work zone. A 5 minute walking mean of the truck flow and total flow result in a truck-share. The truck share of the two detectors is assigned to the observations in the detectors downstream/upstream respectively of the two detectors. The model estimates a influence of minus 20 km/h per truck share. Enforcement shows an unexpected effect of a speed increase of 1 km/h if present, this is an unlikely outcome of the model. The on-ramps have a decreasing effect on the traffic speed, especially an on-ramp in the middle of two work zones. The on-ramp in the middle of work zone 1 and 2 decreases traffic speed with 12 km/h. This is a logical consequence the busy one lane system. The on-ramp in work zone 3 is situated in a two lane system and has a smaller speed reducing impact of 2 km/h. Visible activity is modelled as well and has a speed reducing effect of 3 km/h.

The outcomes of the MLRM are tested and, except for the enforcement outcome, match previously found results. The model shows signs of heteroscedasticity, meaning the error variance of the residuals is not constant. This does not influence the coefficients of the MRLM, but it influences the error terms and the significance level of the estimates. The MLRM shows no signs of multicollinearity or other regression validity problems. Heteroscedasticity can be corrected for, but another model type like a temporal-spatial model may provide even better results. Especially the relationship between the measurement points (repeated measurements) in each work zone should be investigated.

Based on the field trial, the verification of the design requirements and validation of the designs performance, it is concluded that the design looks promising. In the design, the credibility of a work zone is linked to the speed limit and the activity of a work zone. Information is provided to improve the credibility and the speed limit is adapted to the work zone situation. However, it has not been researched if these are the most important factors in the credibility of work zones. Also, it has not been tested if drivers actually read the information provided on the PCMS during the field trial. If it is proven traffic participants read the message, the message can also be optimized. It can be studied which kinds of messages improve the credibility of work zones. Studies which facilitate stated preference of participant for example: driving simulators or (video) questionnaires are better suited for this purpose. And while this field trial uses road side systems, in-car technology may be even more effective in providing this kind of information.

The design method (HSI) proved helpful in the process from problem definition to the validation of the design. The incorporation of human factor elements in a technical design is possible using this method. Especially the emphasis on the project and design risks is important in the design of a human factor incorporated system. These risks are often one of the stakeholders concerns and if one tackles these, the design's chance of successful application is enlarged. The HSI design method could be applied and tested in a more complex technical project. In most traffic systems and in the development of automated vehicles, human factors are important. It is thus recommended to study if the HSI design framework can be useful in this industry as well. Since: *"There is no such thing as an unmanned system"[Brigadier General Don D. Flickinger, Director of Human Factors, USAF]*

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List of Abbreviations

Abreviation	Dutch context	English context
ASAP	-	Appropriatie speed saves all people research initiative
CI		Confidence Interval
ConOps	Operationeel concept(document)	Concept of Operations
CROW	Tegenwoordig: Eigennaam kennisplatform CROW Oorspronkelijk: Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstech-niek	Name of Technology platform for transport, infrastructure and public space
DOT		Department Of Transportation
DS		Driving Simulator
FHWA		United States Federal Highway Administration
HF	-	Human Factors
HSI	-	Human System Integration
ISA	Intellegente snelheids assistentie	Intelligent Speed Assistance
ITS	Intellegent verkeerssysteem	Intelligent Traffic Systems
MLRM		Multiple Linear Regression Model
MONiCA	Monitoring casco	Monitoring Casco
MTM	-	Motorway Traffic Management system
NASA		National Aeronautics and Space Administration
PCMS	Tekstkar	Portable Changeable Message Sign
QSHE	Kwaliteit, Arbeid en Milieu(KAM)	Quality Safety Health and Environment
RP		Revealed Preference
RWS	Rijkswaterstaat	Road authority of the Netherlands
SBS	-	System Breakdown Structure
SE	-	System Engineering
SP	-	Stated Preference
SPIN	Systeem Planning en Informatie Nederland	System of Planning and Information the Netherlands
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid	Institute for Road Safety Research
USAF		United States Air Force
V85	85 percentiel van de snelheid, Operationele snelheid	85th percentile of speed, often called: Operational speed.
VMS	DRIP- Dynamisch Route Informatie Paneel	Variable Message Sign Dynamic Message Sign (DMS) Changeble Message Sign(CMS)
WVL	Wegverkeersleider	Traffic operator

1
Introduction

In the Netherlands, we have a dense and high-quality road network. Every day, work is done to maintain or improve this network so that we all can reach our destination in a quick and safe way. There are numerous types of roadworks: lane closures due to scheduled maintenance, emergency repairs due to an incident or large road closures to expand the infrastructure network. All these types of roadworks ask for a different work zone layout, and they all have a very different impact on traffic. However, they have one thing in common: the road work comes with risks.

In this introduction, the backgrounds of work zones and the Dutch traffic management system are introduced in Section 1.1 and 1.2. The risks following from this system are introduced in Section 1.3. In Section 1.4 the research outline is introduced.

1.1. Work zones

An empty road provides a lot of freedom, what to do with an empty motorway just for yourself? If the motorway is flooded, like in the 1995 flood, windsurfing seemed like a great idea to Max van Noorden. This idea led to the iconic picture shown in 1.1a. But without the circumstances of a natural disaster, a closed motorway can also be appealing. This attractiveness is shown in figure 1.1b, in the also iconic picture of one of the Dutch car-free Sunday's in 1973. Many people took advantage of the car-free situation and biked, organised pick-nicks and moved their furniture to the Dutch motorways.

The last picture is especially appealing to engineers and road workers. Extensive road closures, like that of Figure 1.1c, are a rare event. This kind of freedom is only approved in case there is no other option to do the work. In all other cases, road workers share the road with traffic participants.

(a) Windsurfing on the motorway A2 during flood of 1995 (©John Claessens)

(b) Car free sunday of the seventies (©Wikimedia)

(c) Road closure Dutch motorway A12 (©Rijkswaterstaat)

Figure 1.1: Examples of road closures

Sharing the road is easier said than done, because the traffic speed is high on motorways. Road workers are highly vulnerable because they are often not protected. In order to protect road workers, work zones are created. Three types of work zones are identified: dynamic, semi-dynamic and static work zones. Dynamic and semi-dynamic work zones move with traffic, but are often a lot slower than regular traffic. These kinds of work zones are used for activities such as mowing. Static work zones are the best known kind of work zone. A part of the road is closed for the work, and this is cordoned off by traffic cones, and in case of a motorway, an action car.

The design of work zones is documented in the CROW Guidelines, and follow from the Dutch labour-law. Employers are obliged to create a safe working environment, and the design guidelines are therefore a collaboration between employers, road authorities, training institutes and law enforcement. In the guidelines, a clearance area is described between the workers and the traffic, and the corresponding speed limits are determined. The guidelines also describe how traffic has to be informed such that the speed limit is legal, and the police can enforce those speed limits. On many Dutch motorways the lane signalling system Motorway Traffic Management(MTM) system is used for that purpose.

1.2. Motorway traffic management system

In the Netherlands, the motorway traffic management system was developed and introduced in the early 1980's. The main goal of this system was to prevent secondary crashes in case of crashes or queues [Hagen et al., 2011]. The lane signalling system detects traffic disruptions using loop detectors which measure speed and traffic volume. The Automatic Incident Detection (AID) system as well acts fully automatically. Furthermore, the data of the loop detectors are collected in the national MONiCA system. The MONiCA system consists of 6 regions, equal to the number of traffic management centres (TMC). The TMC's operate the lane signalling system and dynamic message signs.

(a) Dynamic Route Information Panel(DRIP) on motorway A13 (©Rijkswaterstaat)

(b) Work zone and active MTM system on motorway A1

Figure 1.2: Examples of the functioning of the MTM system

Figure 1.2a shows both the MTM signalling system and one of the dynamic message signs. The lane signalling system shows the number 70, the number indicates the currently valid speed limit of 70 km/h. The large road wide information panel gives route information for two directions.

Figure 1.2b shows a combination of a work zone on a motorway with the MTM system. The so called 'arrow-car' or 'action-car' is placed at the start of the work zone. Long before this action car is seen by drivers the lane is closed on the MTM system with a red cross. This is also shown in the background of the action-car where the two right lanes are closed. Next to the action car, which provides a physical safety barrier in the frontal direction, the traffic cones shown in the figure provide a safety barrier in the longitudinal direction. In addition to this short introduction into work zone lay-out, further explanation of the total work zone layout and design guidelines can be found in Section 2.2.

1.3. Problem description

In combination with the MTM system, work zone traffic measures such as the traffic cones and action cars give the road users warnings and information to guide them through the work zone. The goal of the warning system is to decrease traffic participants speed because of the safety of the road workers and traffic participants. There are indications that work zones are more prone to crashes than normal motorway traffic situation[Yang et al., 2015].

This crash proneness can have many causes: a work zone is a substantial deviation from normal driving, and the task may be hard for the driver. Drivers also experience nuisance because of the work zone, next to the expected driving behavioural change they can experience travel delay. Because some drivers are either unwilling or unable to adapt to the traffic situation they speed. Speeding causes new traffic risks, not only for the traffic participants but also for the road workers. In Section 1.1, it is explained that these speed limits were introduced to create a safe working environment. If road users do not adapt to these speed limits, the working environment becomes less secure. This unsafety is experienced by many road workers, as is reported in the research of Kuiper et al. [2007]. Next to risk for road workers, inappropriate speeds also lead to more (severe) incidents according to Nilsson [2004].

Speeding in Dutch motorway work zones leads to large risks for traffic participants and a large feeling of unsafety for road workers. The current situation asks for a practical solution, including the stakeholders' demands. This study aims at designing and testing a new speed management measure for Dutch motorway work zones using a System Engineering (SE) and Human Factors (HF) approach. Including the demands of both road users and road workers in the system design, should lead to higher speed limit compliance. The design will be validated in a field trial, ensuring the behavioural validity of road users and practical feasibility for the road authority.

1.4. Research outline

The research is build up from several components which are explained here. The research starts with a literature review in Chapter 2. This review is used for a better understanding of the complexity of the problem. It also gives direction to the problem scope, and it is used to come up with solution directions for the design.

The insights from the literature review are used to define the research objective, questions and scope in Chapter 3. This study uses both a system engineering and human factors frameworks. These approaches are combined in the Human System Integration (HSI) approach and translated to a practical research design. In the last section of Chapter 3, the research contribution to science and practice is explained.

The HSI work zone design is presented in Chapter 4. The designed system is tested in practice and the method used is described in Chapter 5. In the methodology, the test site is described and the goal of the field trial is presented. The data collection strategies, preparation techniques and analysis methods are explained in this chapter.

In Chapter 7 the field trial results are presented. The methodology of the previous chapter is followed, and the outcomes of these preparation and analysis techniques are presented. The effects of all the new system components are researched individually. Chapter 8 presents the verification and validation of both the design and the field trial analysis. Finally in Chapter 9 the lessons learned from this research are presented, and the research questions are answered. The research implications, practical implications and recommendation for further research are discussed.

2
Literature review

In this chapter the described practical problem is put in an international scientific context, to better understand the problem. Section 2.1 describes the background of traffic safety research. Section 2.2 describes the work zone system. Section 2.3 focusses on traffic safety in work zones. The specific problem of speeding in work zones is discussed in Section 2.4. The driving task in work zones differentiates from normal driving. These differences are explained in Section 2.5. Section 2.6 describes the state of the art of research aiming to prevent excessive vehicle speeds in work zones. These insights gathered lead to an identification of the research gaps in literature in Section 2.7.

2.1. Background of traffic safety

Traffic safety is a societal problem researched from the early 20th century onward. This field of research is centred around the loss of life, and serious injuries, due to crashes. The societal relevance of road safety research is acknowledged internationally by governments and international agencies like the UN. Many express their concerns and goals in road safety targets. These targets are regularly quantified in the number of accidents. However, a risk is a more exact quantification of safety. The quantity of risk depends on both the exposure to the risk and the impact of the risk [Hakkert and Braimaister, 2002]. While in the number of accidents the exposure and impact are often neglected.

In traffic safety research the risk is often called the accident rate, which refers to the number of accidents per exposure. The accident rate is the most objective unit of the variable traffic safety. In practice, it is often infeasible to use due to a lack of exposure data [Nilsson, 2004]. It is possible to identify factors which explain the risk, through empirical accident investigations. Based on these measurable risk factors it is possible to estimate the effect of traffic safety measures. One of these risk factors is speed.

Speed under constant conditions can be linked to crash numbers using the formula of Nilsson [2004] shown in Equation 2.1. In words: the ratio between the number of injuries before and after a change in speed is equal to the square of the ratio between the average speed before and after that change[SWOV, 2016]. If one looks at the number of crashes resulting in a severe injury a power three is used. The number of deaths is described with a power 4,6. This formula of Nilsson means that a speed increase of 10% will lead up to (approximate and on average) 20% more injury crashes, up to 30% more traffic crashes with serious injury and up to 40% more fatal road crashes.

$$\frac{[\text{Number of road deaths}]_{after}}{[\text{Number of road deaths}]_{before}} = \left(\frac{[\text{Speed}]_{after}}{[\text{Speed}]_{before}}\right)^{4,6} \tag{2.1}$$

2.2. Definiton of the work zone system

A work zone is a system designed to separate traffic from the work area. The reasons behind a work zone are various: a traffic incident causing road damage, planned maintenance due to wear and tear or large infrastructure improvement projects causing phased traffic situations. In the Netherlands, work zones are designed according to the CROW work zone guidelines [CROW, 2013, 2014, 2016]. The overview in Figure 2.1 is the typical lay-out prescribed in these guidelines.

Starting in 2007, an extensive practical research project aimed at improving the old guidelines, was carried out in the Netherlands. The research consisted of (in chronological order) a literature review [van Gent, 2007] followed by an accident analysis [Janssen and Weijermars, 2009] and observations/audits of work zones [Weijermars, 2009]. From the inspections, it was concluded that the majority of Dutch work zones did not conform to the guidelines. Especially signs and markings lacked visibility and clarity [Weijermars, 2009].

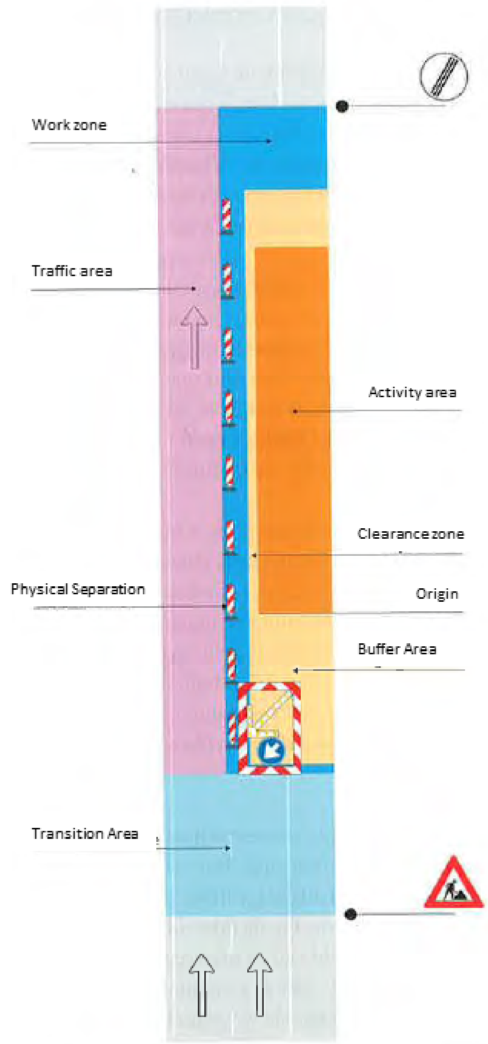
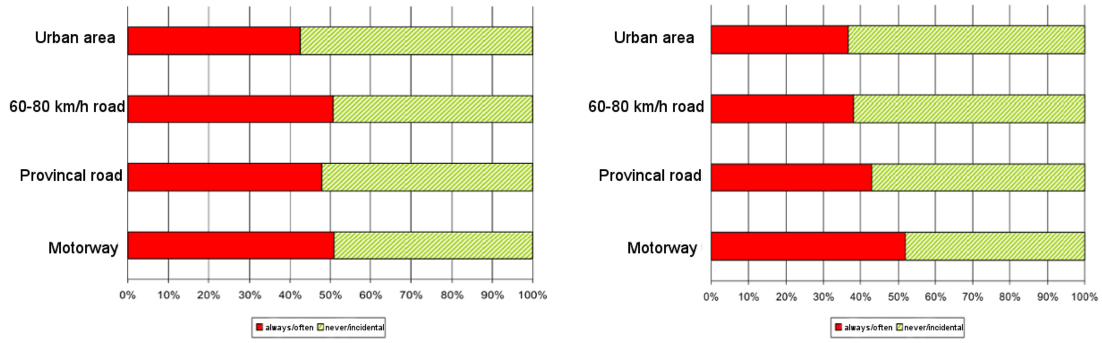


Figure 2.1: Overview of work zone lay-out with definition of terms[CROW, 2013]

Figure 2.1 shows a transition area, in international literature often also an advanced warning area is mentioned before the transition area. In the Dutch guidelines, these areas are incorporated in the same space called the introduction space. For international consistency reasons, the area introduction space is separated into the advance warning area and the transition area in this research. The transition area has three primary functions; inform the drivers, warn the drivers, and set limits and legal commandments [CROW, 2013]. Due to the new information and commandments, drivers have to make adaptations in their driving. Not only their speed has to change, but also a change of direction in the form of a lane change can be necessary. The layout of the transition area depends on several factors: the existing road layout, distance of sight and the other discontinuities like on-ramps.

In the activity area, the type of work is an essential factor. Space needed depends,for example, on working machines. In this area workers are walking, this makes them extremely vulnerable. A buffer zone, therefore, protects the work area in front. The clearance zone at the side has the same function. These zones should be completely free of people and machinery and are used for missteps of both workers and traffic. The activity area, buffer area, and clearance area are all part of the entire work zone. There is also space reserved in the work zone for the physical separation and other traffic measures.



(a) Percentage of road workers which report feeling unsafe due to speeding by road users

(b) Percentage of road workers which report feeling unsafe due to carelessness by road users

Figure 2.2: Road workers safety feeling as researched by Kuiper et al. [2007]

2.3. Safety in work zones

Two major fields of research contribute to work zone safety. The field of work safety and the field of traffic safety. The combination is a logical consequence of the goal of a work zone to facilitate road traffic while facilitating road construction. In the next subsections, both research fields are linked to elaborate on the problem of work zone safety.

2.3.1. Road work safety

The presence of workers introduces the research field of work safety. In work zones, there are two primary types of collisions with a vehicle, a road worker with a traffic vehicle or a road worker with a work equipment vehicle. The collision danger for road workers is severe. Approximately 6 to 7 per 100.000 road workers die due to a collision accident in the Netherlands every year [van Eijk, 2007]. According to the TNO that is the highest deadly incident risk in the whole construction sector [Klauw et al., 2010], which is also the most dangerous work sector in the Netherlands [Kroft and Venema, 2016].

Road workers report the driver behaviour as the most dangerous hazard of collision danger. Especially excessive speeds of drivers are mentioned by respectively, 61% [Debnath et al., 2015] and 71% [Kuiper et al., 2007] of road workers. In Figure 2.2 it is shown that on Motorways workers experience most hazards of road users on motorways. In both studies, the road workers report collision danger with their equipment as less dangerous than the collision danger of passing traffic. This estimation is a typical reaction called the illusion of control described by Slovic in 1987. People are more confident when they believe to be in control. Objective accident studies are inconclusive on this topic. In an accident study of work safety records, the opposite is found, more collision accidents with own equipment occurred [van Eijk, 2007]. This database is biased since crashes involving traffic are often only processed by the police, not work safety investigators. In an accident study of Venema and Drupsteen [2007], it is found that the majority of collision incidents involves traffic participants.

Although both the Dutch study of Kuiper et al. [2007] and Australian study of Debnath et al. [2015] give a new insight into the traffic safety problem, their results are biased by the road workers perspective. The reports emphasise the impact of the speeding problem in work zones for road workers. Also, from this research field it can be concluded that accident data in work safety research lacks detail about the cause of a crash [Venema et al., 2008]. The crash records are spread among companies Quality Safety Health and Environment (QSHE) databases, the national work safety database and the national police database and are therefore lacking consistency [Venema and Drupsteen, 2007]. The same conclusion is drawn from the interview with Berend Brinkhuis in Appendix A.1.

2.3.2. Traffic safety in work zones

In the field of traffic safety in work zones, research is focused on several major areas. Next to work zone typology, driver behaviour in work zones and traffic operations, another field of interest is that of work zone safety and traffic crashes [Yang et al., 2015]. In literature, the increase of crash rate in work zones, compared to no work zone traffic situations varies between 7% [Graham et al., 1978] and 168% [Garber and Woo, 1990]. A small minority of studies found a decrease in crash rate for some work zones [Graham et al., 1978; Jin et al., 2008; Pigman and Agent, 1990]. These large variations suggest that the impact of work zones on the crash rate is still not well understood. These differences are likely associated with factors such as work zone types and traffic conditions [Yang et al., 2015].

On the location, time and severity of crash occurrence in work zones, no consistent results can be found by Yang et al. [2015]. The synthesis of Yang's literature review suggests that on average about 55% of crashes are likely to occur in either the buffer or activity area, as is shown in Figure 2.3. However, lacking exposure data, location data and the wide spread in findings give no conclusive results. Also, literature is lacking consistency in the question whether day- or night work zones are more dangerous. There is also no clear evidence that work zone crashes are more severe than non-work zone crashes. Two dominant and consistent conclusions are that in work zones the accident rates are higher and the speed limit compliance is lower in work zones than in non-work zone situations [Yang et al., 2015] [Torre et al., 2017]. The dominant crash type in work zones is a rear-end crash [Yang et al., 2015] [van Gent, 2007], a crash type which is often related to speeding. According to Hagenzieker [1998], speed is mentioned as the most significant contributor to work zone crashes.

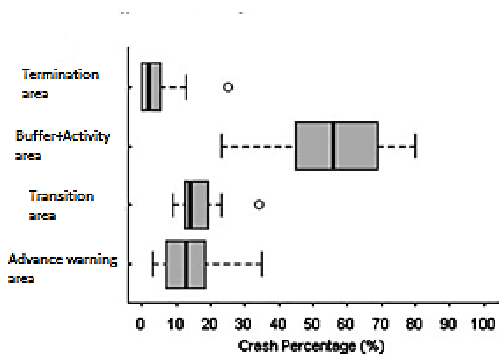


Figure 2.3: Work zone area and corresponding crash distributions[Yang et al., 2015]

In the Netherlands, traffic crashes are monitored in the police crash database BRON. In previous research by Weijermars [2009] it is found that in the period between 2000 and 2009 2% of all registered fatal crashes in the Netherlands took place at roadworks. Especially the number of incidents resulting in serious injury on motorway work zones stands out. Around 4% of all serious injury crashes on motorways are located near or in a work zone. Janssen and Weijermars [2009] did not research the crashes' exact location in the work zone. They did conclude there is a small indication that there is an increase in the share of no-daylight work zone crashes. Towards the severity of the crashes they find especially crashes with serious injury are relatively increasing. Janssen and Weijermars [2009] also showed that in 41% of all crashes speeding was involved.

2.3.3. Conclusion

Although it seems logical to research crashes as they are the consequences of safety problems, it is difficult. Crashes are an abnormality and if they occur the cause is hard to find. This unclear relation is a logical result of the traffic system in which many contributors could cause the crash: the driver, the car or the road. From previous research, it is concluded that it is a combination of these contributors resulting in a crash [Kimber, 2003]. Also with work safety research as a basis, it is difficult to improve work zone safety using crashes/collisions. Since speed is a large contributor to work zone crashes and the feeling of unsafety of road workers, it is more logical to focus on speed limit compliance in work zones rather than work zone crashes.

2.4. Speed limit compliance in work zones

Driver compliance with work zone speed limits is generally poor [Allpress and Leland, 2010; Debnath et al., 2014; Garber and Zhao, 2002; Mohammadi and Bham, 2011], a view is shared by both literature and practice. Excessive speeds in work zones have been a safety concern of road authorities for many years now [Benekohal et al., 1992]. Road authorities express their safety concerns in higher speeding fines for excessive speeds in work zones [Minnesota Department of Transportation, 2014; U.S. Federal Highway Administration]. A Dutch news article in 2014 reports 20% of drivers on the N356 provincial road in the Netherlands received a fine for speeding in a work zone [Transport Online, 2014]. Also in RTL Nieuws [2015] reported an almost 500% increase in fines for speeding in work zones in 2014. The latter suggests that either the level of enforcement increased, the problem grew dramatically or both effects occur. Enforcement figures, however, are biased due to their lack of exposure data. Often authorities are warned for excessive speeds in certain areas. No conclusions can be drawn from them except for the indication of the problem. In the accident study of Janssen and Weijermars [2009], it is found in 41% of the accidents in work zones reported by the police excessive vehicle speed contributed to the crash.

In a recent study of Jellema [2015], work zone speed was measured in 9 work zones on N-roads in the province of Friesland. The operational speed (V85) in no-work zone situation was 10% higher than the speed limit while in work zones this increased to 20-40% higher than the limit. Next to absolute speed, large speed variance also causes less safety and more rear-end accidents [SWOV, 2016]. Two types of speed variation can be measured: the speed dispersion between individual vehicles, and speed dispersion at road section level. In the literature review of Aarts and Van Schagen [2006] several studies are summarised. From 4 case-control studies it is concluded that driving faster than the surrounding traffic, and thus a more substantial speed variance between individual vehicles increases crash rate. Based on two studies which looked into speed variation on the road-section level it is also concluded larger speed variance leads to higher crash rates.

International literature focuses on identifying factors related to speeding in work zones. Which locations, times and other factors are most prone to excessive vehicle speeds? Benekohal et al. [1992] tried to answer this question. They found four categories of drivers. About 63 percent of drivers reduced their speeds considerably after passing the first work zone speed-limit signs (Category 1). Nearly 11 percent of drivers decreased their speed when they neared the location of construction activities (Category 2). About 11 percent of all drivers did not reduce their high speeds (Category 3). The remaining drivers did not indicate a distinct pattern (Category 4). The absence of a definite pattern suggests that in the transition area and the end of the activity area together with the buffer area the number of speeders is high.

One of the only factors which are statistically linked to a reduction of speeders is the presence of construction activity [Jellema, 2015] [Mohammadi and Bham, 2011]. This finding confirms the early research of Benekohal et al. [1992] since drivers only notice action when they are close to or already in the activity area. Blackman et al. [2014]; Steinbakk et al. [2017] found that drivers are frustrated when confronted with a reduced speed limit in combination with no visible roadworks. Blackman et al. [2014] indicated that drivers perceived the traffic signs delivered inaccurate information when no road work was present. This inaccuracy frustrates drivers and undermines the effectiveness of reduced speed limits. Also in a video survey of Steinbakk et al. [2017], it is found that for the videos without visible roadwork activity, drivers stated that they would prefer speeds 7-10 km/h faster than the reduced posted speed limits.

Although drivers, when asked, indicate they would (or should) reduce their speed in work zones [Steinbakk et al., 2017], the objective speed measurements reveal a different picture. In the field of road user behaviour studies, it is researched why this difference between stated behaviour and revealed behaviour occurs and what can be done to influence the driving behaviour.

2.5. The driving task in work zones

For road users, work zones form a deviation from normal driving. Because of the expected driving behaviour changes such as lane changing and the lowering speed, the driving task in work zones is complicated. Behavioural research in traffic engineering is often described as Human Factors(HF) research. Based on literature three major aspects are identified as crucial in describing road user behaviour in work zones. The first aspect is based on perception and attentional aspects and tries to answer the question whether the information provided can be processed by the driver. In information processing theory, driver expectations are discussed as well. Driver expectations play a major role in fast processing and decision making, necessary for the driving task. Although the previously described processes are true for every driver, road users personal circumstances and competence influence these processes. This is discussed in the last subsection.

2.5.1. Information processing

Simply put, driving is a process with input, and the output is (un)intentional driving behaviour. In between, the driver 'is' the system, processing the input and making decisions about his output. More comprehensively, Wickens and Hollands [2000] describe the process of Figure 2.4.

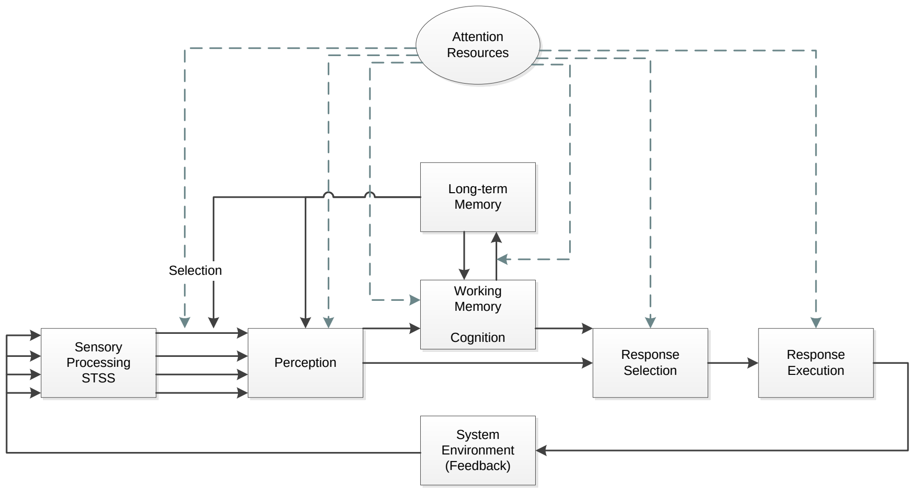


Figure 2.4: Overview of Information processing [Wickens and Hollands, 2000]

The first step in the model is the processing of sensory input(hearing, vision etc.). The next step is to give meaning to the input; the human brain starts processing this information. The processing components are perception, short-term memory and long-term memory. Based on this processing, an action is selected and sent to the motor systems which can execute the selected operation. The process starts over from there since the activities provide new sensory data. Attentional resources give boundaries to the execution of all the processes. Attentional resources are limited and are divided over all work processes in the brain.

In work zones, extra information is provided to the road users. Traffic signs with warnings and commandments are put in place to achieve the desired driving behaviour. Low effects of traffic signs on speeds are well documented in the literature. Roadworks warning signs alone were found to be ineffective in reducing traffic speed [Mohammadi and Bham, 2011]. It could be the case that drivers fail to perceive the information provided (by a lack of attentional resources), as explained in the model above. This failure is however unlikely since a survey study of Charlton [2006] showed road work warning signs are one of the most often detected, remembered and the best-understood hazard warning signs in traffic. Steinbakk et al. [2017] conclude from this that road work warning signs are conspicuous enough, but due to motivational reasons, they are not adequate for promoting safe driving speeds at work zones. Motivational reasons are formed in the central system of perception, short-term and long-term memory. Often in traffic safety research this central system of decision making is translated into driver expectations.

A severe unintentional effect shows in the feedback loop from behaviour to new environmental information. After drivers have driven at high speed for a long time, the road users increasingly underestimate their own speed [SWOV, 2012b]. This underestimation can result in too little reduction of speed in work zones. Also in transition situations from high speeds to considerably lower speeds drivers tend to decelerate too little [SWOV, 2012b]. Both effects apply to work zone situations.

2.5.2. Expectations

Driver expectations are an essential part of the decision making process. They are based on previous experience. A driver receives information and, based on this information, forms expectations about the behaviour of other drivers, the road conditions, the speed limit etc. Based on these expectations the driver decides about his own course of action.

Rasmussen [1983] describes driver behaviour knows three levels: skill-based behaviour, rule-based behaviour and knowledge-based behaviour. In general, driving is often skill based behaviour [Čičković, 2016]. The reaction is automated, and decisions are made unconsciously. If the driver is part of a platoon, and the driver in front of him slows down for a work zone, the driver will also slow down when confronted with braking lights, just based on skill-based behaviour. He does not decide his own speed. The driver follows the platoon.

Rule-based behaviour is a more conscious decision-making process. For example, the drivers perceive a work zone warning sign and know, when this warning is presented, to slow down. This process is more influenced by short-term and long-term memory. Because of the short and long-term memory, a driver expects the hazard presented by the warning sign. Sometimes these expectations work counterproductive and traffic measures lose credibility. Traffic engineers might make the driving task deliberately harder, this is often described as increasing the driving workload. The driver has to be more conscious of his decision making, and this can result in more desired driving behaviour.

In case situations get unclear for the driver they have to process the information and think about the things they, for example, learnt during the driving education. The knowledge-based behaviour and takes a lot of time and effort. During the driving task, there is little time to react so this decision-making stage is very error-prone. Errors and accidents happen if the driving workload is higher than the available work resources. Attention resources are explained by the model of Figure 2.4.

2.5.3. Driver capability and competence

Driving task difficulty is inversely related to the difference between driver capability and driving task demand [Fuller, 2005]. The driver capability depends on many temporary conditions like fatigue, stress and distraction. These psychical and psychological conditions all influence the attention and workload resources. Highway work zones are often deployed during the night, in this period most fatigue crashes occur [SWOV, 2012c]. Fatigue influences drivers' choices and the (speed) decisions. The decisions taken by the same driver during the day may differ.

With driver competence, a more knowledge-based level of task capability is described. It includes personal characteristics, training and knowledge. True motivational choices are influenced by this long-term experience of a driver. Drivers have a negative attitude towards work zones since they usually experience a delay. The deviation from normal driving itself already causes the nuisance. The most substantial contributor to nuisance perception in work zones is the lack of presence of activity in work zones [Glas et al., 2010].

2.6. Speed management

Speed management measures and its framework are used to influence drivers speeding decision. Speed management consists of a combination of policy actions in a logical order [Wegman et al., 2008] [van Schagen and Feypell, 2011]. The framework of SWOV [2016] consists of the six steps described below.

1. Determine the safe speed limit
2. Make sure the limit is credible
3. Give good information about the local speed limit
4. Support the limit with speed inhibitors
5. Police enforcement
6. Education and information

The determination of a safe speed limit is based on the functionality of the road. Which (vulnerable) road users are present, and what are the conflict areas? In the case of a work zone, a temporary situation is created in which new vulnerable road users, road workers, are introduced. A credible speed limit automatically results in high-speed limit compliance. A speed limit is credible if it meets the expectations of road users based on the characteristics of the road and its immediate surroundings [Goldenbeld and van Schagen, 2007].

After a safe and credible speed limit is chosen it is essential to inform the road user about the speed limit. Providing this information in a clear way optimises the predictability of the system. In a work zone, the advance warning area and transition area provide information. The function and layout of these areas are already explained in Section 2.2. One can support a speed limit with local inhibitors. Inhibitors are physical measures limiting speed like narrowing lane width. Police enforcement of speed limits also leads to higher compliance rates. The last action described by the framework is that of education and information, this concerns general information like campaigns and traffic education.

Several suggestions to the framework have been made. Wegman et al. suggest that in the longer term, speed limits should be made dynamic using Intelligent Transport Systems(ITS). Dynamic speed limits lead to flexible and therefore more credible speed limits since they can be adapted to local and temporary conditions[Wegman et al., 2008]. In the SWOV Measures for speed management fact sheet, it is suggested to add Intelligent Speed Assistance systems(ISA) as a final step of the framework [SWOV, 2008]. Next to academic adjustments and supplements, literature also shows a wide variety of applications of speed management in work zones.

In the United States roadside ITS systems are deployed in work zones serving two primary goals: improving safety and mobility. These portable systems typically provide traffic jam warnings, traffic diversion information, variable speed limits (VSL) or travel time information to the road user [Peterson et al., 2015]. To do so, they measure real-time traffic variables like flow and speed. Many configurations and combinations of these systems are tested by various initiatives such as the Smarter Work Zones Initiative (SWZ) of the Federal Highway Administration (FHWA), the Smarter Work Zones Deployment Initiative (SWZDI) of the states of Iowa, Kansas, Missouri, Wisconsin, and Nebraska. Also, independent states Departments Of Transportations(DOT) of the states Utah, South Carolina, and California deploy and research these systems. The FHWA recently provided states with a work zone ITS implementation guide to illustrate how a systems engineering process should be applied to determine the feasibility and design of such ITS work zone systems [Ullman et al., 2014].

In a Californian work zone project which provides traffic jam warnings a significant drop of speed variance was found by Chu et al. [2005], as a side effect. An example of a VSL project is the system deployed in a Utah work zone in 2007. In this system, a dynamic speed limit was used during active work times. During the night, a higher 'no active work zone' speed limit was used. The dynamic speed limit did not result in significant reductions of driver speed during the day. During the night, a variation of driver speeds of 1.6 - 8 km/h was found if static signs were used. If dynamic signs were used the speed variation decreased to 0.8 - 1.6 km/h [Mcmurtry et al., 2008]. In another study into the use of radar-equipped Portable Changeable Message Sign (PCMS) to reduce driver speed by the South Carolina DOT, it was found the 85th percentile of drivers speed was reduced significantly by approximately 4.8 - 16.1 km/h [Sorrell et al., 2007]. The radar-equipped PCMS displayed the speed driven by the road user together with a text message like: "Excessive Speed slow down". Automated enforcement is another example of a speed reducing methods. Benekohal et al. [2009] found that the mean speed dropped below the speed limit when automated enforcement was applied in a Illinois work zone.

Next, to field tests, driving simulator studies are also conducted to test speed management effectiveness. Although modern driving simulators have a high fidelity behaviour of participants in simulator studies is different from real traffic behaviour. Temporal circumstances like weather and fog cannot be simulated. Personal capability constraints of participants like tiredness, illness or stress are not likely to occur in such studies. The effectiveness of measures can be tested by comparing them with the same simulator environment without the measure. The effectiveness of measures tested in a driving simulator is qualitatively valid, however, not quantitatively comparable to field experiment studies.

An example of such a driving simulator study is that of Bham et al. [2014]. In the driving simulation experiment, 4 PCMS's were deployed showing different messages. The speed was reduced significantly after the 4th PCMS. Bham et al. [2014] recommend researching the effect of fewer than 4 PCMS's. Sommers and McAvoy [2013] also deployed a driving simulator for their study into 20 different countermeasures reducing excessive vehicle speeds in work zones. The speed was reduced most if workers were present in the work zone. They also found substantial effects of the presence of construction vehicles, both automated and non-automated enforcement, and required shifting of lanes. PCMS's was the 8th most effective measure out of 20.

As for the EU the Appropriate Speed saves All People (ASAP) project, is a recent example of a research initiative aiming at providing best practices of effective speed management measures [Vadeby et al., 2016]. The European initiative provides a summation of speed management measures to come to a uniform European guideline which is currently lacking. The initiative researched a total of 23 speed management measures and their potential (low/middle/high) for speed reduction given the duration (short term/long term), type of road (motorway/carriageways), and area of implementation (advance warning area/transition area/work zone area). They recommend further research to the delicate matter of deciding the appropriate speed limit, and the effect of combined measures. This research is summarized in the table 2.1.

Table 2.1: Summation of results speed management in work zones

Name	Type of meassure	Summary ASAP	SP workers perspective	RP Driving simulator study	SP driver perspective
		[Sorensen et al., 2015]	[Blackman et al., 2014]	[Sommers and McAvoy, 2013]	[Blackman et al., 2014]
Spot speed cameras	automated enforcement	low-medium	-	high	-
Section control	automated enforcement	-	-	-	-
Driver speed monitoring display	education	low-medium	high	low-medium	medium-high
Variable message sign	education	-	-	low	*
Emotional messages	education	low	-	-	-
Police presence	enforcement	low-high	high	high	high
Static speed limit sign	information	low-medium	medium		medium
Variable speed limit sign	information	low-high	-	low-medium	-
Speed camera sign	fake enforcement	low	-	-	-
Police dummy	fake enforcement	low	-	-	-
Increased penalties sign	information	low	low	-	low-medium
ITS road system	information	-	-	-	-
Chicanes and other lane shifting etc.	inhibitor	-	-	high	-
Narrowed lane widths	inhibitor	low-high	-	-	-
Rumble/Andreas strips	inhibitor	low-high	-	low-medium	-
Optical speed bars	inhibitor	low	-	-	-
Speed camera with worker warning	fake enforcement	-	-	-	-
Flashing lights	inhibitor	-	medium	medium-high	medium

In the Netherlands, research is more focused on the first steps of the speed management framework, a safe and credible speed limit. The national safe system approach, Sustainable safety, views inhibitors as the last cause. On national motorways, a fixed ITS is already implemented preventing research into temporary ITS measures. In 2006, however, a rare field test was conducted on the Dutch motorway with a feedback speed system while drivers vehicle registration number was shown. This direct feedback appeared to result in speed reduction [Cappendijk and Kusters, 2007] [SWOV, 2010]. The system is not a regular Dutch practice and was used once.

A very different approach was taken by Vrieling et al. [2014]. The research focused on reducing driver workload and making a work zone less different from normal driving. In the work zone, design traffic lanes were widened, and the speed limit was increased from 90 to 100 km/h [Vrieling et al., 2014]. On the control road, without a work zone and with a limit of 120 km/h participant drove a mean speed of 115 km/h. In the standard work zone with a speed limit of 90 km/h participants drove 94 km/h. In Vrielings design work zone the mean speed was exactly the speed limit, 100km/h. Vrieling concludes the new design improves speed limit compliance and drivers assessed the new speed limit as more appropriate. According to Vrieling future research should include the worker perspective and feelings of (un)safety.

The most recent research effort is put into in-car ITS, of which better speed management results are expected than roadside ITS [Bazuin, 2017] [van Nes et al., 2010]. Van Nes et al. conclude the tested in-car ITS system achieves the most homogeneous driving speed, an advanced ITS road-side system performs equally well in good weather circumstances. The researched system acceptance of sophisticated roadside ITS was also just as accepted and valuable as in-car ITS.

2.7. Conclusions and gaps

From the literature review, a research scope and problem definition can be identified. In subsection 2.3.3 it is already concluded crashes are difficult to research. Speeding is a useful risk factor of traffic safety explained in section 2.1. It is even more important in work zones than normal traffic conditions since road workers often feel threatened by speeding road users. The impact of a collision between a vulnerable road worker and road traffic is often severe especially in the case of high speeds. The number of crashes in work zones is higher than in normal traffic. Also, excessive vehicle speeds are found more often in work zones.

The direct cause of this dangerous behaviour is not found, yet many contributing factors can be identified. Work zones are an abnormality from regular driving and this irregularity challenges drivers. Although there are substantial indications drivers deliberately speed in work zones, there are also factors which hamper speed limit compliance of drivers. Drivers find it hard to estimate their lower speed when they have driven high speeds for a long time. But then again, cars have speedometers. So it should be possible for drivers to correct for this unconscious mistake.

A lot of international effort is put in testing speed management measures for work zone applications. Actions like police dummies only have a temporal effect. Automated speed enforcement is effective in lowering speeds, but is not favoured by authorities. Inhibitors like speed bumps or chicanes do have a more long-term impact but are challenging to implement on motorways. The most promising speed management effort is increasing the credibility of speed limits. However, large-scale application of credibility theory in practice still requires effort and development [SWOV, 2012a]. For this development, the ITS implementation guide of the FHWA uses the V-model system engineering framework. This model has the potential to improve the Dutch practice as well. However, this should be tested before any claims can be made about their effectiveness in the Dutch setting.

3 Research framework

The vulnerable group of road workers experience an unsafe working environment on a daily basis. Johan[1] is a road worker specialised in traffic measures. He and his colleagues experience angry and speeding road users on a daily basis. Some colleagues even put trash containers by the side of the road to slow traffic down. They put some trash in it and put it on the edge of the road, so it seems like an obstacle. According to Johan car users always slow down because of the potential damage to their car. The trash container trick seems like a strange practice, and it isn't a measure described in any guideline. For Johan and his colleagues, it is what it takes to create a safe working environment.

Research confirms Johan's concerns. In an extensive study of Venema et al. [2008] it is concluded that it is likely that the chance of a fatal collision accident for road workers is larger than the possibility of a deadly accident in the construction sector in general. While the construction sector is already the most dangerous work sector in the Netherlands [Klauw et al., 2010; Kroft and Venema, 2016]. Not only accidents are indicative of safety problems around road work zones. Road workers report an immense feeling of insecurity during their work in the same study of Kuiper et al. [2007]. Almost three-quarter of the survey respondents said they are exposed to speeding traffic always or often. These problems are most significant for road workers in motorway work zones.

On average 18 fatal crashes occurred every year from 2000 to 2009 [SWOV, 2010]. Due to a lack of exposure data, the crash rate in Dutch work zones cannot be determined accurately. This number of fatal crashes count for 2% of fatal crashes in Dutch traffic. This relatively high number is even higher in Dutch motorway work zones Weijermars [2009].

Several research gaps are identified in section 2.7. From these gaps together with the problem described above, the problem definition is stated as follows:

Speeding in Dutch motorway work zones leads to large risks for traffic participants and a large feeling of unsafety for road workers. This immediate problem requires a practical solution. This solution should include the human factors using a system engineering approach.

In this chapter, a framework will be presented for the design of the research. In the section 3.3 two different theoretical frameworks are presented, and one combination of both frameworks is discussed. These frameworks lead to the framework used in this study which is presented in section 3.4.

3.1. Research objective and questions

The goal of this research is to find a practical solution to the problem described in the previous section.

To design and test a new speed management measure for Dutch motorway work zones which improves speed limit compliance by integrating HF requirements into the system design.

[1] Johan Bekendam - Foreman traffic measures BAM Infra Verkeerstechniek [Appendix A.2.1]

Including the demands of both road users and road workers in the system design could lead to higher speed limit compliance. The design will be tested in a field trial, ensuring the behavioural validity of road users and practical feasibility for road workers and road authority. To reach the objective multiple research questions have to be answered. The questions to be answered are stated below:

- How can the current work zone system practice be described?
- What are the HF requirements for an improved system design?
- How can a new speed management measure be designed which integrates HF requirements?
- What are the effects of the designed solution on the traffic system?

3.2. Research scope

Many factors influencing speed limit compliance in work zones were found in the literature review in chapter 2. The factors are summarized in a fishbone diagram in Figure 3.1 and describes the scope of the research .

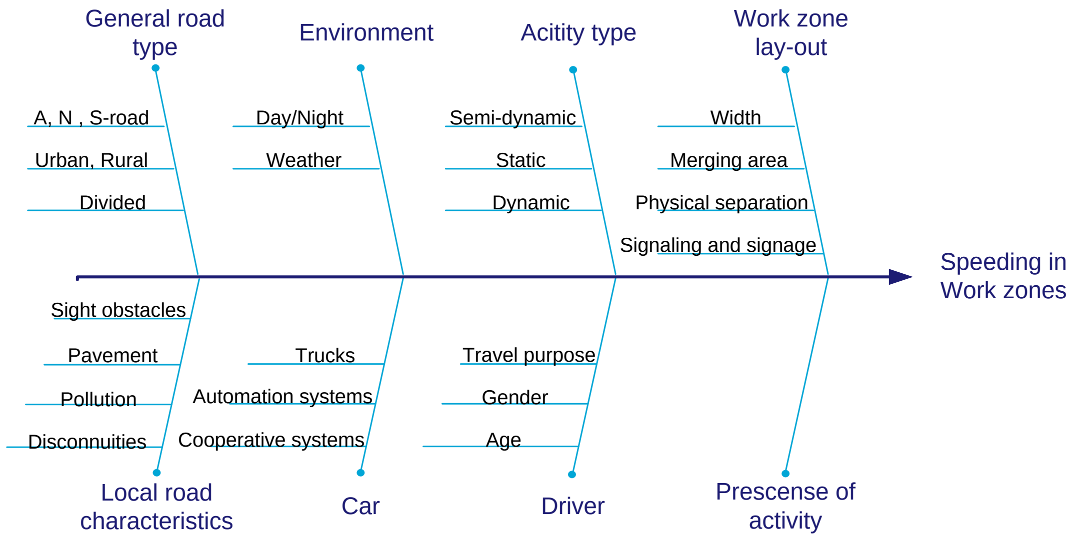


Figure 3.1: Fish bone diagram of factors influencing speeding in work-zones

According to BRON police database, most accidents influenced by work zones happen in the urban area. The most severe accidents, however, happen on Dutch motorways (A-roads). The severity of crashes is a logical effect of the speed impact of accidents, given by the formula of Nilsson [2004]. The chosen general road type for the research are Dutch motorways which, by definition, are rural and divided roads. The largest number of accidents happen during the day. However, this cannot be plotted against the exact number of affected vehicle hours, and so it is impossible to draw significant conclusions. Most work zones are deployed during the night to minimize the delay impact of work zones. Also, excessive vehicle speeds are found during the night. Since the goal of this research is to have a significant effect on this safety problem, nighttime work zones are the chosen research topic.

Three types of work are defined in the CROW guidelines: static, dynamic and semi-dynamic work zones. Most work zones on Dutch motorways are static work zones providing a fixed space for a certain amount of time. Dynamic work zones have far less impact since they travel, with lower speed, in the same direction as traffic. Dynamic and semi-dynamic work zones are not included in the research scope. The work zone layout influences the speed of drivers. The width of the temporary lanes, a concrete barrier or a row of traffic cones all affect driver behaviour. Therefore it is an essential factor in the experiment design. Also, local road characteristics influence a drivers speed. Especially on smaller roads these factors like sight obstacles and pavement type call for different driver behaviour. On through-roads, these elements are standardised as much as possible by design guidelines. Still, discontinuities like curves or on-ramps do influence the operational speed. Because of the research type, the local road characteristics and work zone layout cannot be excluded from the research. It is, however, an unlikely solution direction.

In this research, it is chosen not to focus on specific driver groups or characteristics. Since many kinds of drivers use the public roads, the solution should be usable and useful for every driver. Using the same line of reasoning car characteristics and technology are excluded from the research since many kinds of systems and cars use the public roads and a solution should be suitable for all of them. Furthermore, the commissioner of this study is not able to influence car system. The only available portable in-car system of Be-Mobile NV/SA, has too little coverage in the night [Aarts et al., 2015].

Presence of activity is an essential factor influencing speed limit compliance in work zones, and therefore it should be included in the research solution space. When researching driver speed, the weather is another influential factor. The weather influence cannot be excluded in a field test situation. It is infeasible to influence the weather so it will not be included in the solution.

3.3. Theoretical framework

Two frameworks are essential to the research design. The research field of human factors was already introduced in Chapter 2. System engineering is used in the design of intelligent work zone systems of the FHWA [Ullman et al., 2014]. The two theoretical frameworks can be combined into one framework taking a Human System Integration(HSI) approach. This approach ensures all stakeholders are incorporated into the system.

3.3.1. Human factors design

”Human factors” (HF) is a term used in transportation research to describe the application of knowledge about human information processing, decision making and human task capabilities. The HF research domain is that of road user behaviour and safety. Section 2.5 provides an overview of human capabilities and competence in the driving task. In the speed management framework of SWOV [2016] HF are translated into a more solution-based systematic approach.

All models describing driver behaviour which are mentioned in the literature review have one thing in common, they do not provide an integrated solution for the road system. They work from the perspective of the road user only. The work zone is a system in which many stakeholders and ’system users’ are involved thus this approach only considers a part of the system.

3.3.2. System engineering

The System Engineering(SE) V-model is used for creating an integral system solution. The system engineering approach originates from aerospace engineering and is used in many engineering fields today. In his theoretic book about SE Wasson [2006] defines system engineering as follows:

”The approach defines a system as an integrated set of inter-operable elements, each with explicitly specified and bounded capabilities. All the elements are working synergistically to perform value-added processing to enable a user to satisfy mission operational needs in a prescribed operating environment with a specified outcome and probability of success.” [Wasson, 2006]

In short system engineering ensures that all possible aspects of a project or system are integrated into a whole using a discovery approach. The system engineering design approach can use the system development V-model of Figure 3.2. The V-model describes the following design process:

If a new system is designed, it is important to state its operational missions and objectives. The system has to be defined and bounded. Also, stakeholders need to be identified. These initial steps are

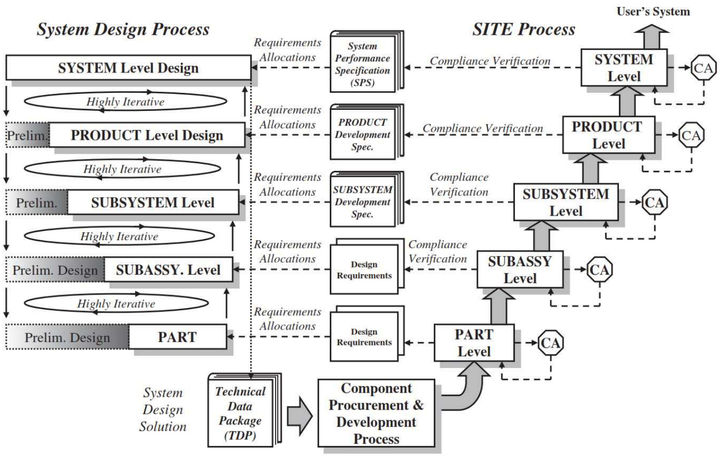


Figure 3.2: Overview of the V-model [Wasson, 2006]

summarised in a document called a Concept of Operations (ConOps). Since the system objective is stated, later on the designed system can be validated. Was the correct system designed? The system requirements follow from the ConOps and describe the technical requirements of the to-develop system solution. These conditions are used to verify if the system is designed correctly. From the functional and technical requirements, a physical solution is created. Until this stage nothing is described as a hardware element, this keeps an open solution space until the final design. This functional and open design approach is called the top-down design method. The execution of the project follows a bottom-up approach. It incorporates fabrication, integration, verification and validation to ensure the maximal system output in the operational and maintenance phase.

3.3.3. Human factors in System Engineering

Although human factor engineering often takes a systematic approach, in the case of traffic safety research it misses out on other system users than road users. The field of Human Systems Integration (HSI) is focused on integration people, technology and organisations at a system level, giving full consideration to human requirements of all the users [Tadros, 2013]. According to the United States Department of Defense, this includes the consideration of personnel, training, safety, health and human factors engineering.

According to National Academy of Sciences Committee on Human-System Design support for changing Technology [2007], there are five key principles to HSI in the system development process. The first is to (1) Satisfy stakeholders, if a stakeholder in an HSI system has a prospect of an unsatisfactory outcome, the stakeholder will refuse to cooperate with the system development. The second and third principle follow on each other: (2) Incremental growth of system definition and stakeholder commitment leads to (3) Iterative system definition and development. (4) Concurrent system definition and development and solution is another key principle, which in SE is incorporated in the process model, for example, the V-model or waterfall method. The last key-principle (5) Risk management is essential in most engineering projects, but risks coming from HSI are often integrated risks.

Tadros [2013] compares HF methodology's and incorporates them in the SE framework. He identifies many possible methods such as incident studies for the concept of operations phase and workload assessments for the design phase. His key conclusion is that there are many types of analysis and methods available from HF engineering for the system engineer. Key is to incorporate the human factors in every step of the SE process. Tadros' framework provides a stepping stone but is far from finished. The application field is that of military defence systems.

A unique HSI framework is made for this research, using Tadros [2013] analysis. In the next section, the framework is explained.

3.4. Research Design

The research design uses a V-model approach which is shown in Figure 3.3. The V-model is adjusted at some points. There already is a work zone system, which differs the ConOps document. It is important to find out the current practice, current system and most importantly, its flaws. These findings are part of the system definition stage. A task description of actors in the current system is performed using an activity swim-lane diagram. Also from an HF perspective, the driving task is assessed in the literature review. The user needs were identified throughout the research using formal interviews, more informal site visit interviews and meetings with stakeholders to arrange for the field test.

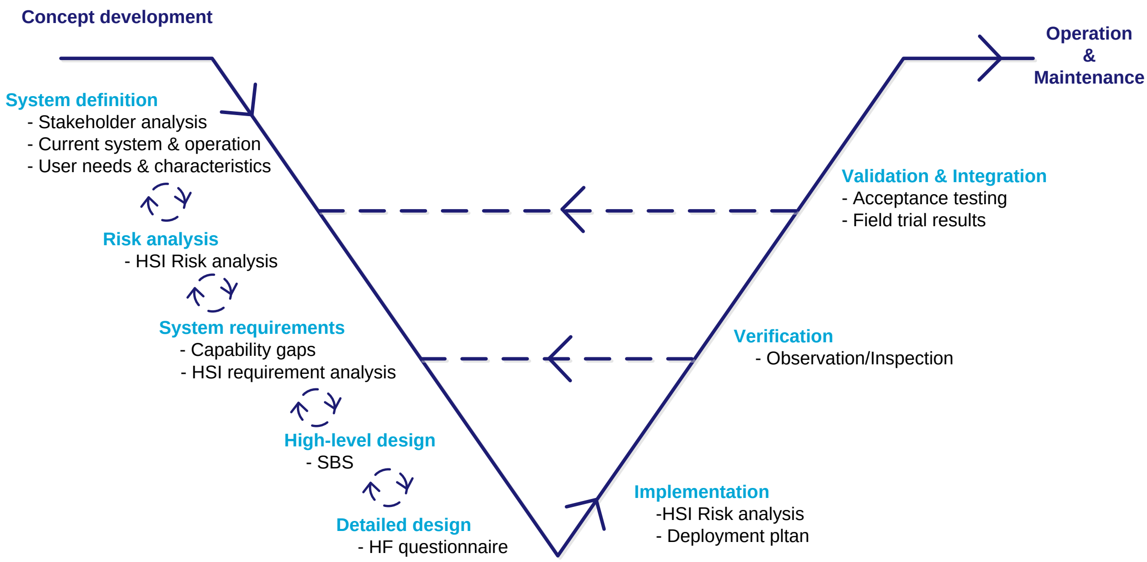


Figure 3.3: Overview of Human System Integration V-model with research design

Different from the V-model described in figure 3.2 a risk analysis stage is added to the V-model. The analysis is added because many V-models do incorporate such a step, for example in the Dutch construction tender practice and the HSI V-model of [Intergo, 2011]. It is important to identify risks of the new system and system tests at an early stage to mitigate those risks. They form a threat to the feasibility of the research field test and the ethical research objectives. The risk register also has an important role in the stakeholder commitment (HSI design key principle 5) and the continous iteration ensures the system objectives are met. The risk analysis performed is documented in the Risk Register which is part of the deployment plan of the field test it is a document used throughout the process.

Defining system requirements can be a very time-consuming process. It is out of the scope of the research to define all the exact system requirements since only the MTM system will have many hundreds of requirements (e.g., the MTM system shall have an availability of 98%). The focus of this research is the HF system requirements following from the task analysis and user needs. This process is described by Tadros as an HF requirement analysis. Often a scenario analysis or storybooks are used for this HF requirement analysis [Tadros, 2013]. This research uses a scenario analysis which is performed using different road user types defined by Benekohal et al. [1992].

The high-level design does not use specific HF methods. The detailed design uses a user-verification of the design, in the form of a questionnaire. After the design phase the implementation and Verification/Validation phase follows.

There are three primary research methodologies for testing driver speeds in work zones: surveys, driving simulations and field trials. The most important reason to chose a field test is the behavioural validity of drivers. From a human factors perspective, especially the behavioural validity of drivers is essential. The personal competences and capabilities defining the 'normal' behaviour are influenced by an experimental environment like (video) surveys and driving simulators. Emotions and situational behaviour described by the capability level(like haste) are difficult to incorporate in a test environment. Also, competences of drivers are not simulated correctly in such an environment. Drivers are incapable of stating which speed they would drive based on video's or pictures. Driving simulators lack feedback systems like car and steering movements which is an essential factor of the competences component of driving behaviour.

In the implementation and integration phase, a field trial is performed which is used to validate the design. Next to traffic measurements described in the next section also observations are used to improve the validity of the test and to incorporate an HF approach. The observations of the field trial are used for verification of the requirements. The results of the field trial are used to validate the design. The systems operation and maintenance phase is not part of this study.

3.5. Research contribution

Safety-related research always aims at societal benefits. The described feelings of unsafety during the daily job of road workers leads to stress. The caused stress may have large health effects. This does not even include the health effects of incidents in work zones. In Section 2.3.2 it is proven work zones increase the incident rate. It has a reason work in this direction is often sponsored by road authorities, health organisations and other governmental organisations. The problem has a large societal impact, and if the current research can improve this, the public will benefit.

Apart from a large societal benefit, the research contributes to both science and practise. These are summarized in Figure 3.4.

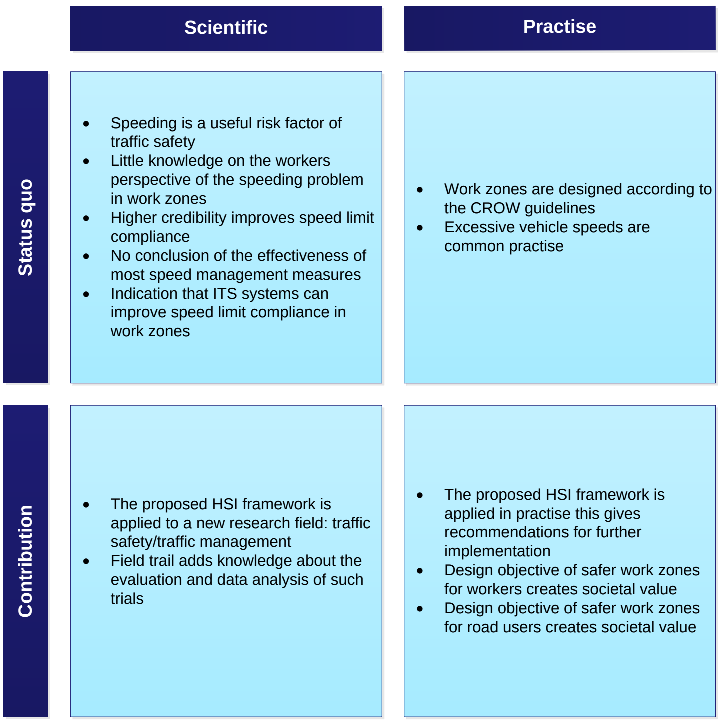


Figure 3.4: Overview of status quo and contributions of research

4 System design

This chapter describes the design process using an HSI V-model approach. First the system scope is defined in Section 4.1. All the stakeholders are identified in Section 4.2. Then the concept of operations (ConOps) of the current system is explained in Section 4.3. In Chapter 3 the justification and nature of changes to the current system are already explained. The justification of changes will be elaborated on in the user needs Section 4.4. From the User needs design requirements are stated in Section 4.5, and these are used for the proposed system design, described in Section 4.6.

4.1. System scope

As described in Section 2.2, a work zone has two main functions: facilitate work and facilitate traffic. Both functions have to be fulfilled in an efficient and safe manner. There are reasons to believe the safety of the current system can be improved. The most important reasons are excessive vehicle speeds reported by objective measurements and by road workers.

The system mission is to facilitate work and traffic in a safe and efficient manner.

The research objective described in section 3.1 already provides system boundaries. These boundaries are further explained in the research scope which can be found in section 3.2. In short; it is chosen to focus on work zones on the national motorway. It is also decided to focus on a system which would be available for and has an impact on the general public. That is why roadside systems seem to be most logical solution direction in the current environment since in-car technology with advanced possibilities, does not have a high enough penetration rate yet.

In Section 5.2 site of the field trial is described. Although the design should be implementable for every Dutch overnight lane closure, the specific legal nature of this road stretch differentiates the entities involved. The A12 road stretch is part of a Design Build Finance and Maintain (DBFM) project owned by a Special Purpose Vehicle (SPV). The implications of this legal construction are explained in Subsection 4.2. The practical aim of the design is to improve speed limit compliance in a typical Dutch overnight lane closure on the national motorway A12.

4.2. Stakeholders

In November 2011 the Dutch newspaper 'De Telegraaf' published an article about safety in work zones. Questions were sent to the Dutch minister of infrastructure Schultz van Haegen [2011]. In her answer, she mentions the entities who are responsible for safety in work zones. Road users are responsible for their driving behaviour and contractors and their personnel are responsible for safe and functional work zones; also labour unions and employers associations have a responsibility. The road authorities are responsible for issuing safe orders. The national government should make regulations, set boundaries and enforce those. On a high level, this gives an overview of all parties involved in the work zone system.

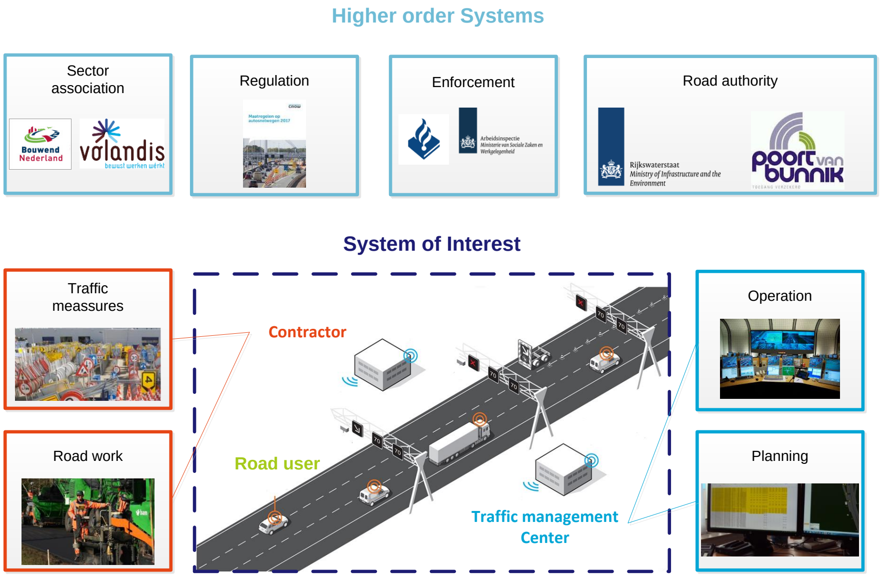


Figure 4.1: Overview of scope and stakeholders (adapted from[Rijkswaterstaat, 2015])

A party which is not mentioned by the minister is the system maintainer. In a DBFM construction, a system maintainer is introduced. The SPV 'Poort van Bunnik' is responsible for incident management and maintenance during the life cycle of the DBFM contract. The SPV maintains all hardware in the infrastructure project. If an incident happens, immediate repairs are necessary to meet the requirements of functionality and safety of the road. These requirements are issued in the contract by the road authority, or system owner, and is in case of incidents often expressed in response time deadlines. Except for incidents, there are two other major causes for road construction: scheduled maintenance due to wear and tear, and large infrastructure improvement projects which involve phased road construction work. In both cases, the performance indicator is not response time but vehicle loss hours. The SPV hires a contractor for each of the described types of work. Often it hires the contractor that is also the owner of the SPV. In case the road is not part of a DBFM, the road authority is also system maintainer.

As explained by the minister other higher-order parties include enforcement, regulation and sector associations. In the case of a work zone, two stakeholders with a judicial role are active: the police responsible for traffic regulation and labour inspection responsible for labour conditions. The CROW guidelines regulate work zone design, sector associations are involved in education and research and Bouwend Nederland is the association for Dutch contractors. Volandis is an institution for knowledge about labour health and safety. Unlike the CROW, it does not create legal guidelines but its primary tasks are to advise and research. Rijkswaterstaat(RWS) is mentioned twice in Figure 4.1. RWS is both the road authority and the road operator. The traffic management centre of RWS is responsible for the operation of the traffic management system MTM.

Contractors are a primary stakeholder in work zones. The traffic measures department is specialised to plan, design and construct the work zones. They function as a system shareholder since they contribute to the system development. The road workers who do the road work an place the traffic measures are system users. Within the contractor entity also supporting departments/systems are active: Quality Safety Health and Environment(QSHE), traffic managers and environment managers.

The last stakeholder in the system of interest is the road user. The design of the traffic system should be such that it is safe and functional for the road user. Models that describe the interest and behaviour of the road user can be found in subsection 2.5.

4.3. Current system

This section provides an overview of the current system. Identifying the current work zone system was not straightforward since the information is not widely available. Since 2017, a so-called uniform work process is available which is used in all VWM-regions [Rijkswaterstaat, 2017].

4.3.1. Background, objectives and scope

In the Netherlands, the Intelligent Traffic System (ITS), MTM, was developed and introduced in the early 1980's. The main goal of this system was to prevent secondary crashes in case of crashes or queues [Hagen et al., 2011]. The lane signalling system detects disruptions using loop detectors which measure speed and traffic volume. The automatic incident detection (AID) system acts fully automatically in case of a detected incidents. The data of the loop detectors is collected in the national MONiCA system. The MONiCA system consists of 6 regions, equal to the number of traffic management centres (TMC). The TMC's operate the lane signalling system and many dynamic message signs which provide route information.

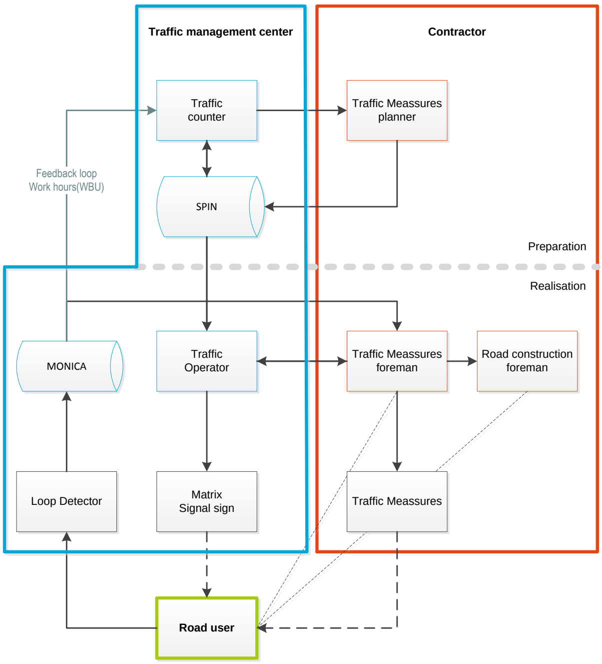


Figure 4.2: Overview of current system

In the case of road construction, a layer has to be put on the MTM system manually by the traffic operator. The lane signalling system has to close lanes (show red crosses) and lower the speed limit. This lane signalling system is changed in a specific layout, and that is planned in a design system. The planning system is called System of Planning and Information the Netherlands (SPIN). Many stakeholders and support systems (communication department, surroundings managers etc.) have access to SPIN but in the system of interest of this design four roles are recognised. Their operations and activities are explained in the next section. Their connection with SPIN can be found in figure 4.2.

If the MTM system is not available, contractors work with physical road work signs. This situation changes the traffic measures necessary to create a safe work zone. The work zone is physically guarded in longitudinal and vertical direction. In the longitudinal direction, traffic cones are used. In the vertical direction, a so-called action car (or arrow car) is used. The combination of these two form the temporary traffic measures.

From the literature review, we know that the sight of a lowered speed on a matrix signal sign and temporary traffic measures affects the last essential stakeholders, the road user. The effect is shown in figure 4.2 by a 'not physical interaction' dashed arrow. Also, the presence of activity affects road users. Since this effect is unintentional and not organised in the system, the relationship is sketched using a dashed line.

4.3.2. Operation of the current system

The operation of the current system is described in the activity diagram of figure 4.3. SPIN is used for the planning of work zones. The traffic measures planner of the contractor creates a SPIN request. The SPIN request is digitally sent for approval to the traffic counter (the short term planner) of RWS. In the case of approval, the traffic measures planner can start preparing the work zone. In case the design is not approved the request has to be redesigned and approved.

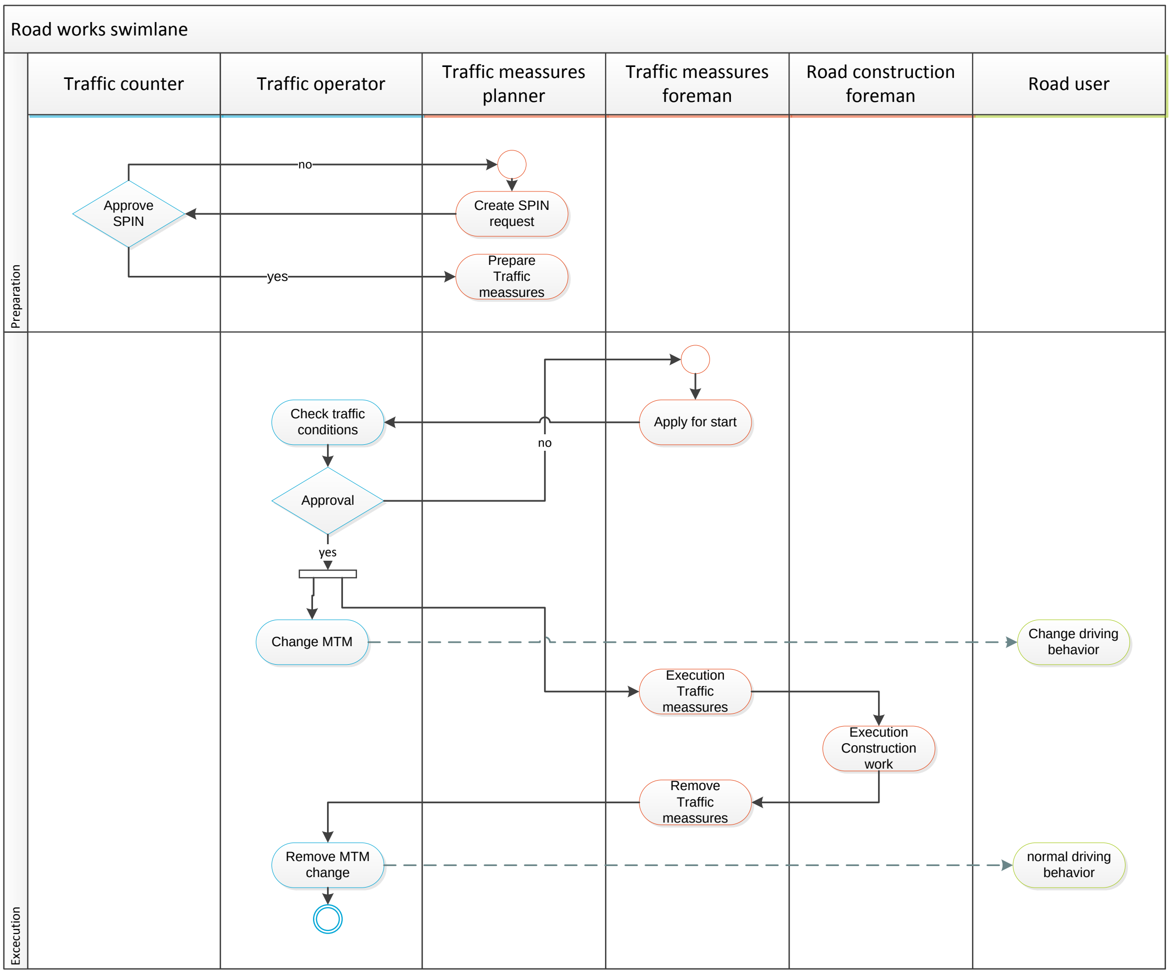


Figure 4.3: Swimelane activity diagram of current system

At the start of the planned work, the traffic measures foreman contacts the RWS traffic operator. If, as expected, the traffic has decreased enough the start is approved. The time expectation of low traffic is expressed in the workable hours which can be found in the SPIN request report. If the request to start is approved by the traffic operator, the MTM system will be changed according to the design of the SPIN request. The speed limit is lowered, one lane is closed and the foreman can now start building the work zone. For safety reasons, a truck with a shock absorber and flashing arrow sign is used. The other truck places the action car without shock absorber behind the first truck and the Andreas bars are placed. Also in the longitudinal direction traffic cones are placed. When the work zone is complete, the traffic measures team contacts the road construction crew. The road construction crew can now enter the work zone. It depends on the exact work zone layout, but often the crew enters by a merging action between the traffic cones. Often the crew enters by a merging action between the traffic cones. When the construction crew completes their work, they contact the traffic measures team and leave the work zone. The traffic measures team removes the cones and action car again using their shock absorber safety truck. After they left the work zone, they contact the traffic operator to remove the MTM measure.

In this system, it is expected drivers change their driving behaviour (slowing down, switch lanes) based on the MTM signals. In this research, the problem definition mentions excessive vehicle speeds. The problem of crashes with the action car is not part of this study. These collisions, especially their high number, are an indication the MTM signals are lacking conviction for drivers to change their driving behaviour. Together with the problem definition, this asks for a different system design.

4.4. User needs

In subsection 4.2, three system users are found who all have different needs. The combination of user needs will lead to a user-centred design solution. The user needs are identified using literature and informal interviews in practice. These interviews include meetings with Rijkswaterstaat to arrange for the field trial, construction site visits and a more formal interview with an expert in the field of road work safety.

4.4.1. Road workers needs

Road workers are professional system users. They follow the different protocols to execute their work, and this results in relatively uniform user behaviour. Behavioural excesses are often aimed at efficiency improvements but lacking safety considerations. Using the clearance zone or buffer area for ’a quick fix’ are examples of such behavioural excesses [Venema et al., 2008]. These excesses illustrate one of the needs of road workers: workspace. Their ultimate working environment would be a closed road. No bother of traffic would give enough space for equipment, resources and themselves. According to road workers, a closed road would be the safest working environment. Road workers feel threatened by the other system user, ’road users’. They cannot influence the road users behaviour and a lack of control results in considerable feelings of unsafety.

Flexibility is another need for road workers. Although road workers are professional system users, road work is a typical do-job. The unpredictability of construction work is a well known, but debatable, factor in the industry. This unpredictability results in very flexible workers with a hands-on mentality. Examples of the need for flexibility are flexible access to equipment and resources.

In this study, three work zone conditions are identified which create extra hazards for road workers: placing traffic measures, merging in and out of the work zone area and removing the traffic measures. Due to the flexibility need of workers, merging work traffic is an often occurring event which can be a hazardous situation for both work traffic and regular traffic. The placement and removal of traffic measures is a job which takes a lot of caution [Volandis, 2016]. The workers operate close to traffic as is shown in figure 4.4. If a worker works closer to traffic or is doing a job which asks for caution, workers are more bothered by the speed of traffic participants.

4.4.2. Road operator needs

Road operators are also professional system users, they behave according to the different protocols. Road operators approve requests and monitor the work situation. Since they control large areas, they need an efficient and safe system. This system can not take a lengthy work protocol as road construction activities are only a small part of their work. The monitoring system and the user interface for the road operator is outside the system scope.

4.4.3. Road users needs

Road users are both professional and non-professional system users. This changes road user needs. For non-professional users training to achieve better system performance is often infeasible. Also, road users feel less obliged to follow specific rules or procedures. Benekohal et al. [1992] found four

Figure 4.4: Example of placing traffic management measures on a Dutch motorway (source: handels- en Verhuurbedrijf Krans B.V.)

categories of speed-reduction patterns of vehicles in a highway construction zone. They did not find a significant difference in speed reduction patterns between professional road users(truck drivers) and non-professional users.

Road user needs in work zones are researched by the 'Minder hinder team'(less nuisance team) of the Dutch road authority RWS. Glas et al. [2010] mentions five possible themes of work zone nuisance in order of importance: (1) no visible activity, (2) travel time delay, (3) information/Communication, (4) detours and (5) layout of the work zone. Within these hindrance themes specific aspects are identified, the top five consists of aspects in which the road user cannot relate to the actions/choices of the road authority or contractor [Glas et al., 2010]. Road users cannot relate to the aspects of the length of invisible work activity, traffic jams due to work zones, late warnings about road work, etc. These feelings are often expressed in sentences like: 'How could the road authority/contractor ever arrange something like this, I could've done it better myself'.

Another major conclusion of Glas et al. [2010] research, and therefore a guideline in road authority practice, is that road users dislike road closures. They prefer multiple weeks of one lane closures over one week of a total road closure. Road users prefer night work over weekend work. These preferences are the exact opposite of the road workers who prefer road closures because of their safety and flexibility. Finding the safest type of road closure is not the goal of this research. This difference of preference is important to mention since it is a significant point of frustration towards road authority and road users, especially for the road workers.

4.5. System requirements

The newly designed system should address the issues discussed in the problem definition. After the collection of the user needs and the analysis of the current system capability, the system gaps can be identified. These capabilities may lead to new functional system requirement or non-functional system requirements.

4.5.1. Capability gaps

The current system is not able to perform some capabilities which are needed by the system users, these are called capability gaps. To address the stated problem of low speed limit compliance, behavioural changes are necessary. These are explained in Figure 4.3. The causes for lack of road use behaviour change can be found at the road users themselves.

From the literature study, it can be derived the credibility of work zones in the Netherlands is low and road users find hindrance aspects they do not understand most frustrating. A credible speed limit means that the limit is consistent with the expectations evoked by the road layout so that drivers are more inclined to keep to the limit [SWOV, 2012a]. The credibility of a speed limit in a work zone is dependent on more factors than the road layout. The most substantial contributing factor to the credibility of work zones is the activity in a work zone. The absence of activity in a work zone is the most significant contributor to the nuisance of road users [Glas et al., 2010]. Finley et al. [2015] shows the speed of drivers decreases more if the first speed limit sign is within view of the work zone condition. In this case, the road user can see an direct relation between the work and the sign. According to van Gent [2007] and Weijermars [2009] dynamic speed limits in time, space and even lane may improve the credibility of a work zone. More dynamic speed limits are also a recommendation of Jellema [2015], who researched speed limit compliance and recommended to use dynamic speed limits since: *'only signage is not enough'*.

The credibility of a work zone seems to have a relationship with invisible work activity and the incomprehensibility of the need and implementation of the work zone. Not only the stated speed limit is essential, but also information and comprehensibility seem to play a role in user needs. This need can be combined with a need of the road workers. They work with one work zone and one speed limit in one night, while the work zone has multiple conditions and even various crews. For example, the placement of traffic measures is a work zone condition (and crew specialism) in which workers work far closer to traffic than in the regular work zone situation. Information about the work zone condition may increase the credibility of a work zone.

There are however limitations to the human performance of drivers which should be discussed. The possibility for drivers to process information during the driving task is limited. Drivers reduce speed if the workload of the driving tasks becomes too high, they reduce the workload. This incapability is especially relevant in a motorway context due to the high driving speeds. Drivers are weak in assessing lower speed when they have driven at high speed for a long time. Their awareness of their speed is low. During the night the driving task is already more laborious and drivers experience fatigue.

A credible speed limit often means that drivers can relate to the designed speed limit. A work zone is a big distraction from a standard road situation in which credibility is therefore a complicated factor. Setting the right expectation about the work zone condition may increase the credibility of the work zone. However adding information in the driving task has a disadvantage of creating a higher workload. Also with high vehicle speeds, the road-side information may be missed.

4.5.2. Functional requirements

Functional requirements are requirements which describe capabilities. The main function of a work zone is to facilitate both construction work while also facilitating traffic. For these two main functions 'facilitate traffic' and 'facilitate construction activity' several lower level functions have to be performed by the system. This includes guiding and informing traffic participants. For the work area, both the physical work area and the access to this area need to be facilitated by the system. Because the two functions interact, the interaction needs to be addressed in so-called interface requirements. In Table 4.1 these interactions are addressed by stating new functions. It is not the research goal to exactly state requirements following from each of the functions for example: 'change traffic course' because the technical requirement of such a function would be the road providing a specified amount of friction.

Table 4.1: Functions of work zone system

Function	Sub function
Guide traffic	Lower traffic speed
	Change traffic course
	Provide throughput
Inform traffic	Issue commandments
	Warn for danger
Facilitate work access	Provide low speed for course change
	Provide course change for work traffic
Facilitate work area	Facilitate storage of equipment
	Facilitate use of equipment
	Facilitate storage of materials
	Facilitate work space
Prevent interaction	Lower traffic speed
Mitigate interaction	Provide frontal physical buffer
	Provide longitudinal physical buffer

4.5.3. Aspect requirements

Aspect requirements is a term used for 'non-functional' requirements. Aspects are essential for a system, but without stating these requirements the system can function. The system is however unlikely to be useful if it is not safe or cannot be maintained. In System engineering the RAMS requirements well-know non-functional requirements. RAMS is an acronym for Reliability, Availability, Maintainability and Safety. Many letters have been added to this acronym, such as Health and Environment.

Table 4.2: Aspect requirements of the work zone system

Aspect	Requirement
Credibility	The work zone condition shall meet the drivers expectation
	The traffic shall be informed about the work zone condition
	The speed limit shall be adapted to the work zone condition
Operational effectiveness	The workload for the traffic operator shall be within a operation time of 10 minutes
	The workload for the foreman traffic measures shall be within a operation time of 10 minutes
	The system shall be explainable within 15 minutes of training for the traffic measures foreman
Safety	The system must be designed to eliminate or mitigate safety, health or physical risks.
	Identified safety an health risks will be eliminated, minimized or controlled to acceptable levels(...) within cost, schedule and performance constraints.
	The system design and operational plan shall be approved a QSHE coordinator
	The system design and operational plan shall be approved by the road authority
HFE*	All human engineering aspects shall be in compliance with current HF Engineering research and coordinated by a Human Factors Engineer*

It is out of the scope of this research to state all aspect requirements of the system. From the user needs and capability described in sections 4.4 and 4.5.1 respectively, HSI aspect requirements follow. The most important new HSI aspect is 'credibility'. The requirements following from this aspect ensure the work zone condition meets drivers expectations. To do so, the road users shall be informed about the work zone condition. The (dynamic) speed limit shall be adapted to the work zone condition as well.

The aspect of operational effectiveness follows from the user needs of the road operator and road worker. It is infeasible to provide those parties with new training for one experiment so the new system should be explainable within a small time frame and fit within the existing system operation. For the traffic operation centre, it is essential operators do not suffer a work overload so the operation time should be minimised. For the traffic measures foreman, the explain-ability is important. The operation of the new system was explained to the traffic measures foreman via a written briefing which can be found in Appendix C.3.

Safety is a well-known aspect in SE. The first requirements described with the safety aspect ensures the project uses a risk analysis approach. Risk management is an integral part of a successful HSI project [National Academy of Sciences Committee on Human-System Design support for changing Technology, 2007]. In this scientific study, it is crucial to ensure an ethical test situation. That is why the approval of a non-involved QSHE coordinator and the road authority are essential. More details about all the safety-related risks of this project can be found in the Section 4.6.2.

The last requirement in Table 4.2, for the aspect HFE, is a requirement which is not explicitly met during this research project. The researcher is a traffic engineering student with knowledge of human factors. The requirement is an example of a more process-related requirement which obliges documents or resources to be involved in the project. An example of such a requirement could be to force the project organisation to create an HSI document [Muralidhar, 2008]. An HSI document does not only includes the human factors engineering discipline but all parties involved with human behaviour and human interfaces. In a typical civil engineering project this would involve the QSHE department, the traffic management department and the stakeholder management department. These are standard non-design departments which typically only have a reporting relationship with the system design [Muralidhar, 2008].

4.6. Proposed system design

A design is created using the stated system requirements. The new function 'inform traffic about work zone condition' asks for adoptions to the existing system and operation. The new function is coupled to a physical performer, which is described in the system architecture. The risk analysis is part of the system design and gives input to the operational system. In the detailed design aspect, requirements of the new functional requirement are discussed and tested using a HF method, a HF user questionnaire.

4.6.1. System architecture

The new functional requirement 'Inform traffic about work zone condition' has to be coupled to a physical performer. Multiple physical systems would be suitable to perform this function. Especially in-car systems seem to have these capabilities and are effective. Testing these systems in a field trial is infeasible as these technologies are not proven technology and the penetration rate of these systems is still too low [Aarts et al., 2015]. In this field trial, it is chosen to use a Portable Changeable Message Sign (PCMS). All physical elements which are part of the system are described in Figure 4.5.

4.6.2. Risk analysis

Risk management is an important part of system design, and especially in HSI design. Risk analysis determines the levels of likelihood, consequence and overall risk for each identified candidate risk, and then categorises and prioritises the risks to select risk handling actions [Hall, 1998]. One can identify two levels of risk management, the high-level process risk management and lower-level aspect requirement risk management [National Academy of Sciences Committee on Human-System Design support for changing Technology, 2007].

The concept of process risk management is also used in the arrangements of the field trial. The risk of not getting approval for a field trial was one of the most substantial risks in this project. By including all stakeholder needs, this risk was mitigated. It proved extremely useful to involve both tactical stakeholders, like the planning department, and operational stakeholders. This can be linked to another fundamental principle of HSI design, principle (1) stakeholder satisfaction.

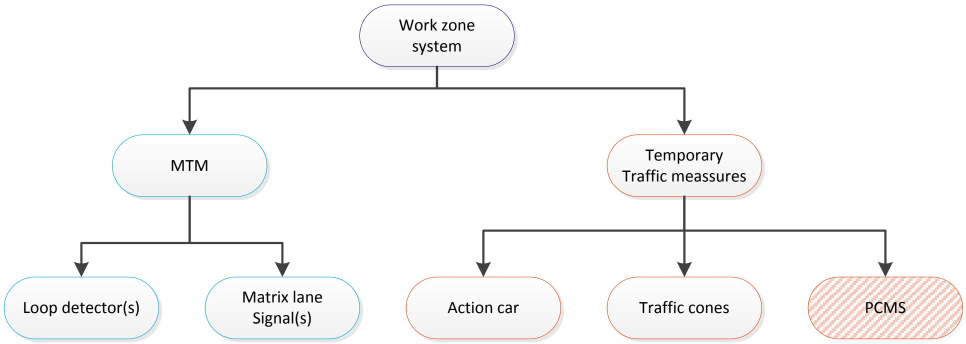


Figure 4.5: Physical system breakdown structure

The finer course grain risk analysis was specified for the field trial. Many factors can contribute to a failure of a field trial, and these risks were analysed and mitigated in a field trial risk register which can be found in Appendix C.2. Three types of threats were identified: safety risks, experiment control risks and system control risks. Safety risks include a potential increase of incidents due to a lack of clarity in the experimental situation. The system control risks are training and operation related risks and technical risks like the failure of the PCMS. This is a logical consequence of the design method since both technical elements and HF are included in the system design. All kinds of factors like enforcement, bad weather etc. can influence the speed data of the experiment, these are called experiment control risks. In case these factors arise, it is more difficult to evaluate the field trial.

4.6.3. Operational scenario

The PCMS is added to the system and should be operated as well as the dynamic speed limit. The operation of the physical system attributes is described in this operational swim lane diagram in Figure 4.6. The researcher is added to the swimlane because it was easier if all other roles focussed on their already widened task. For the operation of the PCMS, an online platform is used.

The traffic measures foreman has to communicate more often. Next to calling the traffic operator also the researcher has to be informed of a new work zone condition. This is an operational risk described in the risk analysis.

From the road user more often a behavioural change is expected. Where in the old design only one system informs the traffic participants about the work zone, in this configuration the MTM system and the PCMS are expected to affect road user behaviour. This relation is shown by the dashed connection lines.

4.6.4. Detailed design

For the detailed design, several lower-level requirements have to be met. These requirements specify how the function 'Informing traffic' should be performed. These 4 requirements are specified in the guidelines of Crow [CROW [2017] , CROW [2016]] and shown in Table 4.3. The aspect requirement 'comprehensibility' is complicated to meet if one designs a new system for traffic participants. This was the reason to test this requirement before the design was tested in a field trial. A questionnaire was spread among 32 participants within the researcher's acquaintances, none of whom are traffic professionals. The participant's age ranged from 20 (students) to 50+ (acquaintances of parents). The original questions and results of this questionnaire can be found in Appendix B

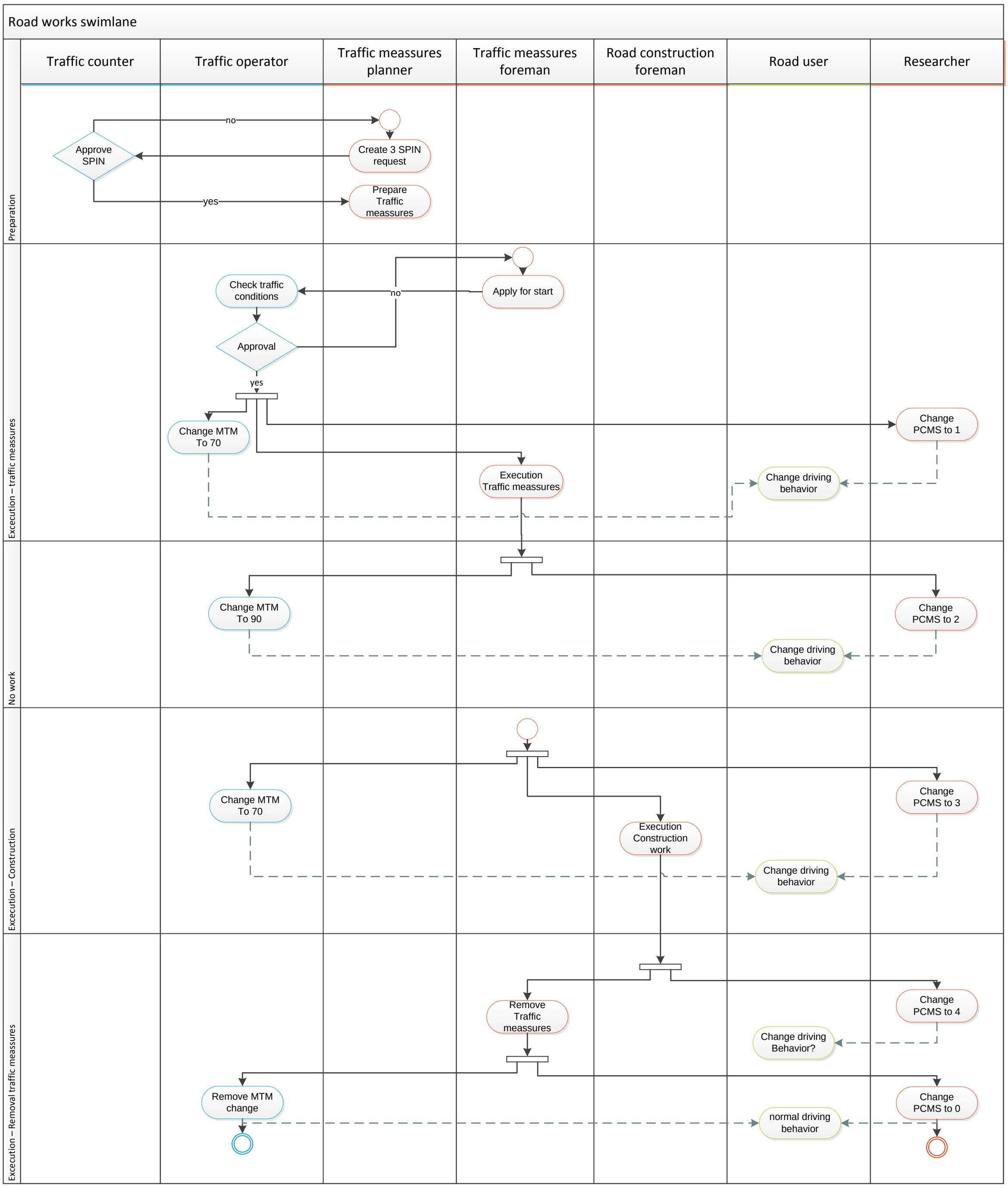
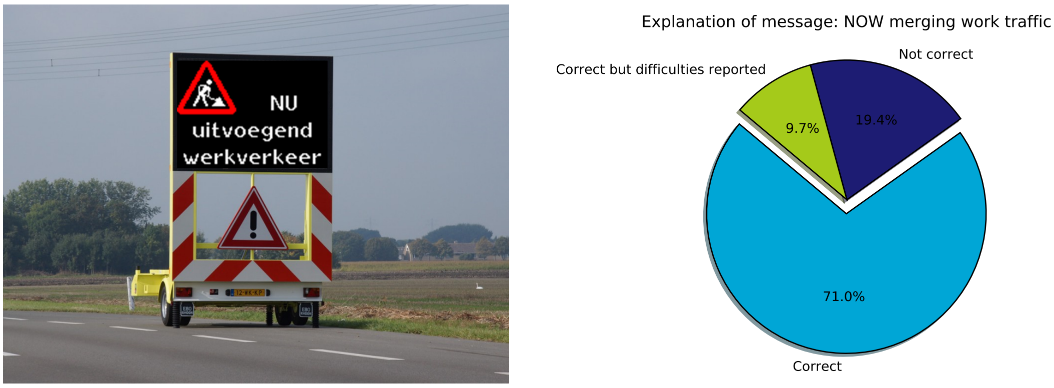


Figure 4.6: Swimelane activity diagram new design

Table 4.3: Aspect requirements of the function: Inform traffic)

Aspect	Requirement
Visibility	The information components shall be placed as described in guideline CROW [2016]
Readability	The information components shall meet the font size specified in guideline CROW [2017] The text shall meet the word lenght standard described in guideline CROW [2017]
Comprehensibility	…
Feasibility of manoeuvre	The information components satisfy warning distances specified in guideline CROW [2016]

The first question was an open question testing if participants understood the message, as shown in 4.7. A time indication was used in this message because the researcher believed this was better comprehensible than without a time indication. The majority (71%) of the respondents understood the traffic management message.



(a) Question example: If you find this sign next to the motorway, do you understand what it means? please explain.

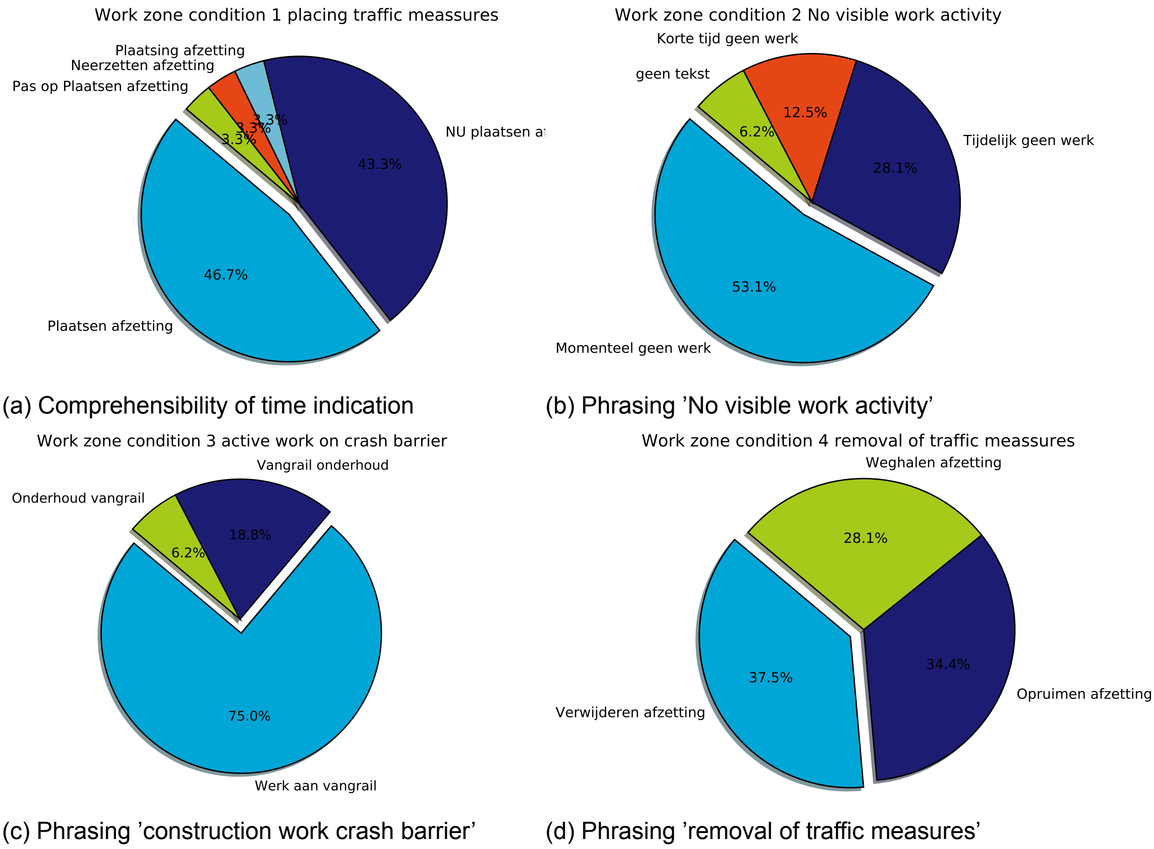
(b) Analysis of question

Figure 4.7: Question about the comprehensibility of work zone conditional information

The second question tested the comprehensibility of an urgent time indication in the message. It was a multiple choice question with a fill-in possibility, and the analysis is shown in 4.8a. The majority (46,7%) of participants preferred no time indication in the message 'placing traffic measures'. Three different texts were proposed by participants: Watch out placing traffic measures, 'Putting down traffic measures' and 'Placement traffic measures'. 46.7% is only a small majority over 43.3% and a larger research population should be used to determine whether or not to use an urgent time indication. However, that is not part of this studies scope so the majority choice, no time indication, is used in the design.

The third question involved the phrasing of 'no visible work activity'. The options were (translated as literally as possible): 'currently no work', 'temporary no work', 'short-term no work'. Via the open fill in possibility, 2 participants suggested leaving the PCMS empty. As shown in figure 4.8b the majority of participants choose 'currently no work'. The phrasing question of the work condition of the work zone resulted in a large majority of 'work on construction barrier'. Although two independent people suggested in the open fill-in possibility to switch 'Crash barrier maintenance' to 'Maintenance crash barrier'. This other phrasing may have resulted in a more equally divided preference. The last question about the phrasing of the removal of traffic measures condition also resulted in a very equally divided preference. The small majority of 12 participants (versus 11 and 9) choose 'deleting of traffic measures' over 'get out traffic measures' and 'Clearing traffic measures'.

From this small questionnaire, it cannot be concluded which text is best comprehensible since most majorities are too small. The population of the questionnaire is also too small. Whether or not the exact text is indifferent regarding comprehensibility is also not possible to conclude. It seems some texts are indeed comparable regarding comprehensibility. There were far more possibilities to phrase the condition than tested in the questionnaire. A traffic management message should be comprehensible



(a) Comprehensibility of time indication

(b) Phrasing 'No visible work activity'

(c) Phrasing 'construction work crash barrier'

(d) Phrasing 'removal of traffic measures'

Figure 4.8: Overview analysis of comprehensibility test

and readable in a short timespan, and short words are preferred over large words. On that basis, the texts were designed by the researcher. The participants of this questionnaire also preferred those short words. This effect is shown in 4.8c where 'work' was preferred over 'maintenance'. It was chosen to follow the majority of the questionnaire for the final design of the traffic management message. The final design is shown in 4.9.

One participant suggested adding the text: 'Watch out'. The warning 'watch out' is already included in the design in the form of the picture of the work zone warning. This image is added to the text of the design because Charlton [2006] found it is a very effective figure. It is one of the most often detected, remembered and best understood traffic signs. In the guidelines for providing information on dynamic information panels [CROW, 2017], it is stated that a red triangle (versus the white square) should be used if the work zone is immediately approaching. Since this is the case, the red triangle work zone warning sign is used in the design.

4.7. Conclusion

After the HSI V-model follows an experimental approach. During this research it proved useful to use the first and fourth principle of HSI design: stakeholder satisfaction and risk management. An important example of such a choice is to include the aspect of operational effectiveness in the design. By searching for the stakeholders opinions about these aspects and including their opinion, the field trial would not be rejected on the basis of operational difficulties.

In the iterative design process three major choices were substantiated:

- The speed limit is differentiated in time, not in the length of the work zone.
- The speed limit was heightened to 90 km/h.
- Four work zone phases were identified

The first choice about the exact realization of a more dynamic speed limit was based on two conversations, one with Rijkswaterstaat and one with BAM traffic measures. It followed that the work zone length was chosen based on the real length necessary for the work. If the length was differentiated on the basis of the location of the work the crew would lose flexibility in for example storing materials[Appendix A.3.3]. It may also become unclear for the workers in which part of the work zone which safety 'clearance zone' was valid and this would be contradictory to the work safety regulations.

The speed limit in the no activity situation was heightened to 90 km/h. 100km/h may be a more favourable option because traffic participants still recognise 90 km/h as a work zone speed limit. Most drivers do not know that normally they would have to drive 70 km/h in this particular work zone. This is because the effect of the type of work, needed clearance area etc., is not known by drivers. Because of this a speed limit of 100km/h would be more favourable to emphasise the 'no work' texts also comes with a heightened speed limit and indeed make the speed limit and work zone more credible. This was however technically impossible in the MTM system [Appendix A.3.1].

The last design choice was made after the questionnaire. In the first night of the trials, the researcher observed that the 'merging work traffic' occurred too often and for a very short time period[Appendix C.4]. Because the PCMS was located too far upstream the traffic message 'merging work traffic' was excluded and four work zone stages remained. These four stages are shown in Figure 4.9

(a) Placement of traffic measures

(b) No visible work activity (with adjusted speed limit)

(c) Standard work situation with work on crash barrier information

(d) Clearing traffic measures

Figure 4.9: Overview of detailed information design after comprehensibility test

5
Field trial methodology

The field trial is performed in the implementation stage of the research in order to test the design. The design of the tested solution is explained in Chapter 4. The limitations of a field trial to test the design are discussed in Section 5.1. The exact location of the field trial is described in Section 5.2. The hypothesis in Section 5.3 contains 'the why' of the field trial. What is the expected result of such a trial? To find these results, data is collected and analysed. The strategy of collection, preparation and analysis is discussed in Sections 5.4, 5.5 and 5.6 respectively. To test the findings the statistical Mann-Whitney U test and the multiple linear regression method are used. These are explained in Section 5.7.

5.1. Limitations of field trial

In this research, a field trial is chosen because of the behavioural validity. Speeding in work zones, especially in night circumstances, is hard to evoke in simulated environments. Field trials are a rare event in the Netherlands, two projects have been found which investigated the topic of speeding in work zones [Ministerie van Infrastructuur en milieu, 2007; Vrieling et al., 2014]. Since the last research in 2014, many new insights and technological developments have arisen.

Although a field trial ensures behavioural validity, several limitations result from this kind of test. A significant deficiency is the design has to use proven technology. Technology which is not available yet should first be tested in simulations before being deployed in a field trial. Some design requirements may be hard to meet with this approach. Future technologies, especially in the field of in-car technology, may fulfil the requirements in a more adequate or efficient manner. This research can give recommendations towards the improvement of efficiency and future implementation of these technologies.

The field trial is a valid case study, but a case study limits the possibilities for general conclusions. Also in this field trial, a novelty effect can be expected. The PCMS might slow down the drivers because they have never seen such an object, instead of the original purpose of sharing information. When using proven technology this novelty effect is not likely to be large but it could be significant. The possibilities for data collection are also limited, which is explained in Section 5.4.

Another important limitation is that in a field trial the possibilities to influence the operating environment are limited. A trial differs from a test or experiment on this point. According to Wasson [2006]: *"Testing employs a prescribed set of operating environment conditions using test procedures approved by the acquirer."* Besides the influence of the operating environment, a test or experiment is a verification method to prove if certain requirements are met. A field trial is a validation method to see if the several sub systems preform such that the overall system goals and user needs are met [Wasson, 2006].

A difficulty when researching human behaviour is ensuring an ethical project. To ensure behavioural validity the possibilities for notifications are limited. Road users are not informed and there are little to no options for informed consent. Introducing a new combination of systems, also with the use of proven sub-systems, creates possibilities of a work overload. A work overload for drivers can have fatal consequences and these concerns have already been addressed in the design phase risk analysis which can be found in Section 4.6.2.

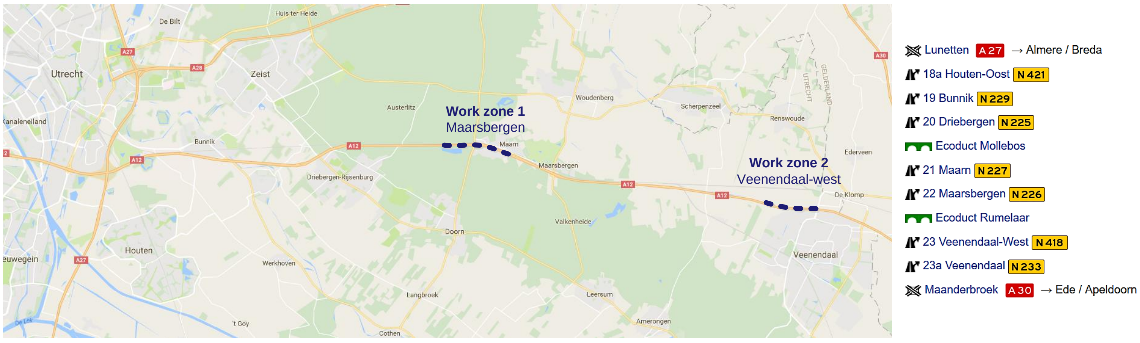


Figure 5.1: Overview of test site work zones (Adapted from Google Maps and Wegenwiki.nl)

5.2. Selection and description of sites

The field trial is performed on the Dutch motorway A12. A typical Dutch motorway is a multiple lane road where the two traffic flow directions are separated by a crash-barrier on both sides. The national speed limit on motorways is 130 km/h. On the motorway A12 from interchange 'Maanderbroek' in the direction of Utrecht interchange 'Lunetten', two work zone sites are used to facilitate the test. One work zone is situated after on-ramp Maarsbergen and the second work zone is situated after on-ramp Veenendaal-west. The location of the work zones is explained in Figure 5.1 and the two sites are described in Table 5.1.

As shown in the table the hectometres run down; this is because the work zones are situated on the left side of the A12 in the direction of Utrecht. In this road stretch, the A12 has three lanes. There are two normal lanes in the middle (r2) and on the right (r3), while the left lane (r1) is a so-called peak lane. It is a more narrow lane which is opened in case of high traffic flows. If the peak lane is open, the speed limit on all the lanes of the A12 is lowered to 100km/h. Both work zones experience a hindrance class of 1 (low) during the work night. Because of the low hindrance class, the 'peak lane' on this road stretch will not be opened during the trial. The work zones will thus have a maximum of two lanes, r2 and r3.

Table 5.1: Overview of work zones sites in numbers

begin ramp	end ramp	begin (hm)	end (hm)	first loop detector(hm)	last loop detector (hm)
Maarsbergen	Driebergen	78.45	75.00	77.8	74.5
Veenendaal-west	Oudenhorst	89.85	87.15	91.4	86.7

In both work zones, the same type of work is executed. A part of the crash-barrier is lowered to make sure the crash-barrier keeps its retaining function. Because the same kind of activity is performed, the same sort of equipment and vehicles are used. These large vehicles and work equipment have an impact on the speeding behaviour of drivers.

It is common practise to request 2 nights of work for unexpected circumstances. These two work zone sites are also planned twice. Since the test is performed 'in practice' it is not clear in advance if and which of the two work zone sites will be repeated.

Table 5.2: Overview of requested and used work zones

Work zone	site	begin	end
1	Maarsbergen	20-6-2017 20:10	21-6-2017 04:20
2	Maarsbergen	21-6-2017 20:00	22-6-2017 03:30
3	Veenendaal-west	21-6-2017 20:50	22-6-2017 04:30
~~4~~	~~Veenendaal-west~~	~~22-6-2017 21:00~~	~~23-6-2017 04:30~~

In table 5.2 the overview of the requested work zones for the lowering of the crash barrier can be found. For the field test work zone Veenendaal was chosen for simplicity reasons, the on-ramp in the work zone in Maarsbergen gave a more complicated layout. The field trial plan was to compare work zone 3 and work zone 4 to study the effect of the new design. The execution of work zone 4 was not necessary and although it is not preferred, a comparison with the different site 'Maarsbergen' has to be made. This summary is shown in Table 5.3. For consistency reasons, the work zones will be numbered in the order of the summary table from now on.

Table 5.3: Summary of work zones

Number	Site	Night	Disconinuties	sign
1	Maarsbergen	Tuesday	On-ramp	no sign
2	Maarsbergen	Wednesday	On-ramp	no sign
3	Veenendaal	Wednesday	-	sign

5.3. Hypothesis

The data should be analysed to study the effect of the new work zone design compared to the normal work zone design. The general design goal was to design a more credible work zone to lower the amount of speed offenders. The expected increase of safety provides a societal benefit. However, road works feel especially unsafe due to high speeds, so they do not notice small mean speed differences. These high speeds should be investigated to evaluate the effect of the new system on the road worker.

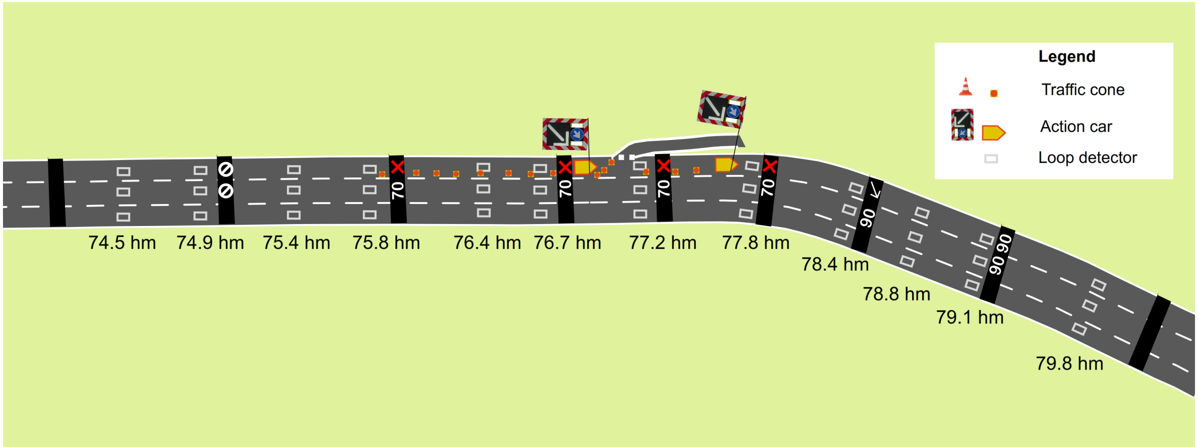
A sign is added to the system design and thus it should be researched if and where the road users react to this new sign. It is expected the sign influences the speed negatively and the length of the effect is limited. From the dynamic speed limit, which is increased from 70 km/h to 90 km/h in the no activity phase, an increase of speed limit compliance is expected.

5.4. Data collection

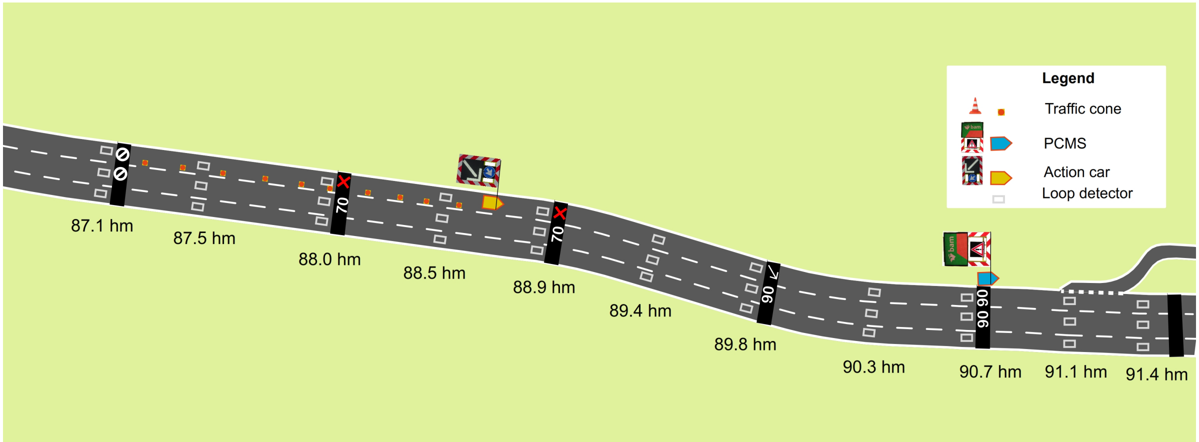
Three types of data are collected during the field trial. Two types of data are collected using the loop detectors available in the work zones. The loop detectors on the A12 are installed every 300 to 500m on every lane. The loop detectors sent aggregated minute mean speed and flow data to the central assembly point, eventually ending in the traffic management centre via the MONiCA system. The data collection points of the loop detectors are shown in Figure 5.2.

An important flaw in the usage of loop detectors with minute aggregation is the impossibility to identify vehicles in platoons. Platoons are vehicles driving in a train with a headway of less than or equal to 4 seconds [Debnath et al., 2014]. Drivers in platoons distort speed limit compliance measurements since they do not choose their own speed . Even the first driver of the platoon is influenced by the drivers behind him. A different approach has to be sought to overcome the disability to identify platoons.

Another important flaw of the use of inductive loop detectors is that they overestimate speed [Knoop, 2016]. The speed overestimation is caused by the moving observer principle. Suppose there is a



(a) Work zone 1 and 2 Maarsbergen data collection locations



(b) Work zone 3 Veenendaal-west data collection locations

Figure 5.2: Overview of loop detector locations (hm) for data collection

local loop detector located at $x_{detector}$. We reconstruct which vehicles will pass that detector within the aggregation time(t_{agg}) of one minute. For a vehicle to pass a loop detector at location $x_{detector}$, that vehicle has to be closer to the detector than the distance it travels in one minute:

$$x_{detector} - x_i \leq t_{agg} v_i \tag{5.1}$$

For faster vehicles ($> v_i$), the travel distance in one minute is larger. Thus if one takes a local mean, the influence of faster vehicles is larger and the average speed v_t is overestimated. This research does not use travel time computations and the fundamental relation of $q = ku$ is not used for calculations. Therefore time mean speeds, although overestimated, are sufficient for measuring effects of the proposed design.

On detector points 76.7, 77.8, 90.7, and 91.4, a more elaborate loop detector system is installed. This system also collects vehicle length data, dividing the speed and flow over three vehicle categories:

1. Vehicles of $\leq 5.6m$
2. Vehicles $5.6m - 12.2m$
3. Vehicles $> 12.2m$

Thus for every vehicle category the aggregated speed and flow per minute, per lane are collected. During the experiment 10, full colour video cameras were available in each work zone. The images of these cameras combined with work crew communications lead to observation data. This data is used to filter out discontinues like police enforcement in the data preparation. Next to this observational evidence, the operational SPIN data is available for the researcher. This database provides the exact times at which the automatic MTM system is overruled by the planned work zone layout.

5.5. Data preparation

Before the collected data can be analysed, the data has to be processed. The Excel™ sheets with MONiCa data have to be combined into one data set. Other data sources like observations and the date of the vehicle categories have to be added to the overall data set. Then the data has to be categorised to overcome comparison difficulties.

For the preparation of data and the analysis of the data, the Python™ computing environment is used. Python™ is a universal programming language which can be used for scientific data analysis. Python™ 2.7 is used and visualised using the Spyder development environment which is heavily MATLAB™ inspired. The *pandas* package provides useful data analysis tools, the *numpy* API is used for numerical computations and the *datetime* package provides means to process the temporal indication in the data spreadsheets. The last relevant Python™ API is the *matplotlib.pyplot* package used for visualising the data in plots. It is not the goal of this research to program this data analysis most leanly or optimise the code in any way.

5.5.1. Filtering

Data from the MONiCa system is made available by RWS for this research purpose. The data of 20-6-2017 00:00 until 22-6-2017 23:59 is gathered. Loop detectors on a closed road stretch give a speed measurement and flow measurement of ’253’ or ’-1’. Of course these are incorrect and the numbers are used to filter the data. Using the flow contour plot the detectors can be checked for consistency. If a detector reports less flow and gives a discontinued image, the detector is considered defect and will be excluded from the research.

From the observations, other risks like enforcement may appear. These should be treated with caution the data analysis since these circumstances may cause beneficial results for speed limit compliance which cannot be assigned to the treatment.

5.5.2. Adding data

Next to data which has to be excluded based on the observations, the data provided by the MONiCA system misses two types of data. The speed limit of a manually overruled MTM portal is not stored in the MONiCA data-sheets. Only in case the automatic traffic jam detection system becomes effective, speed limit data is stored in data sheet. The speed limit at a certain point at a certain time can be determined from the SPIN system, as it overrules the MTM system. The data is extracted from the SPIN code, after which all data points are assigned a speed limit based on spatial and temporal characteristics.

Two loop detectors in each work zone detect vehicle categories. This data is analysed, but also added to the ’normal’ loop detectors. The flow per vehicle category is used to create a percentage of vehicles in each category. The mean flow per hour is used as an overall representative measure of the three vehicle categories in the work zone. The detectors which measure the vehicle category flow are located before and after the on-ramps. Both have one ’normal’ detector located in between which is at the location of the on-ramp. All loop detectors situated upstream of the first vehicle length detector are assigned to this vehicle-length detector. All loop detectors downstream of the second vehicle length detector are assigned to the vehicle length detector downstream of the on-ramp. The detector in between both vehicle length detectors is assigned to the upstream detector since this is the last known vehicle category percentage.

5.5.3. Categorize data

Traffic flow and speed are strongly related, this relation is described in the fundamental relationship:

$$q = ku \tag{5.2}$$

This formula describes that a certain density k (veh/km) times the speed u $(km/hour)$ is the flow q $(veh/hour)$. Equation 5.1 already explains that this is only the case if the space-mean speed is used instead of the time-mean speed. The fundamental diagram of Figure 5.3 visualises the fundamental relationship.

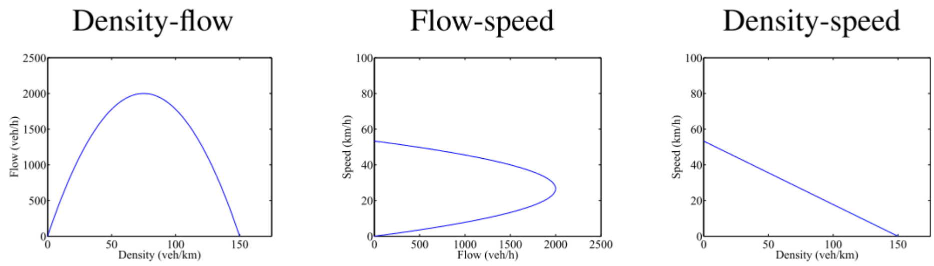


Figure 5.3: Greenshields [1934] fundamental diagram [Knoop, 2016]

The relationship explains that if the traffic becomes denser, the speed will drop because of the maximum road capacity. From a certain point, a traffic jam will occur which creates very low speed and very little flow. Until that point, the relationship describes that a lower flow has higher traffic speed and higher flow has lower traffic speed.

When comparing speed data, it is important to account for this relationship. That is why the data is categorised into four flow categories. For each loop detector measurement, it is known how many vehicles in that lane passed the loop detector and which aggregated mean speed those vehicles had. The data is categorised by the detected flow ($(veh/min) * 60$) into four categories:

1. High flow = ≥ 600 vehicles/hour/lane
2. Middle flow = 300-540 vehicles/hour/lane
3. Low flow = 120-240 vehicles/hour/lane
4. Individual flow = 60 vehicles/hour/lane

The categorisation is based on the measured data, the data is categorised in such way that a reasonable number of observations is put into each category. This categorisation helps in explaining the platooning variable. A flaw of the usage of loop detectors is the inability to identify platoons. Categorisation of flow does not overcome this issue, since the speed of individual vehicles and platoons cannot be determined. In the low flow category, there is a smaller chance the cars were driving in a platoon. In case of an individual flow of 60 vehicles per hour, only one vehicle is detected in that one minute and 1 speed is measured. These measurements have the most significant chance to be free from platoons. But even these 'individual flow' measurements are not free from being influenced by a platoon. The data is categorized per minute, so it is possible for a platoon of two cars to be split into two individual measurements if they pass the detector right at the minute mark. Thus it might seem that there are two individual cars, but in reality it is a platoon of two cars.

5.6. Data analysis strategies

Before the effect of certain designed measures can be investigated, the work zones should be compared regarding the spatial-temporal data available. In this non-controlled environment many other factors influencing the speed measurements are identified. First, a method has to be identified to compare the work zones in spatial and temporal terms. What detectors in which work zones should give a comparable speed profile? What are the exact temporal phases in the various work zones?

5.6.1. Temporal comparison

In the temporal comparison it is important to identify which time frames have a different influence on the speed measurements. Work zone 1 and work zone 2 have the same spatial dependency but the work zones near Maarsbergen are divided over two different nights. The flow during in the night is very temporal dependent and decreases over time. The flow categorisation accounts for all expected effects on the speed measurements, but is should be investigated if this assumption is right. This is researched in Section 6.3.2. The speed limit is changed over time in work zone 3, this is shown in Table 5.4. The layout of this changed speed limit can be found in Table 5.7. In columns MTM Signal 1 the layout of work zone 3 situations where the speed limit was 70 in the activity area. In the column MTM Signal 2 the situation is shown in which the speed limit was 90 in the activity area.

Table 5.4: Begin and end time of work zones

Work zone	Begin time	End time	Speed limit activity area
1	20:10	04:20	70
2	20:00	03:30	70
3	20:50	21:07	70
3	21:07	21:28	90
3	21:28	04:30	70

From the SPIN database and the observations, different work zone phases are identified in Table 5.5. In the experiment, road users are informed about the work zone phase and as already explained the speed limit is differentiated. This difference in information and speed limit makes the work zone more 'dynamic' and perhaps more credible as well. To study this effect of the dynamic speed limit and the PCMS text, the work zone phases can be compared in time. In case of phase 2 in work zone 3, the speed limit was higher and to account for that the comparison should be based on speed limit compliance.

Table 5.5: Work phases based on SPIN database and observations

		Work zone 2		Work zone 3	
Phase	Activity	Begin	End	Begin	End
1	Placement of traffic measures	20:03	20:22	20:53	21:06
2	No visible activity	20:23	20:25	21:07	21:28
3	Working on crash-barrier	20:26	03:11	21:29	04:18
4	Removal of traffic measures	03:12	03:29	04:19	04:27

5.6.2. Spatial comparison

The spatial setting of work zone 1 and 2 are shown in Figure 5.2a. The layout is summarised in Table 5.6. The advance warning area starts with the 90-90 signal, after which the 90-↙ signal follows. This signal is the start of the transition area. Because of the approaching on-ramp, several 70-X follow in which the right lane is already closed but activity has not yet started. In this area, the traffic of the on-ramp can merge into the middle lane which is opened. The activity area continues from 76.7hm to 75.8hm, after which the traffic measures stop while the MTM system still shows a work zone. At 74.9hm, almost one kilometre downstream, the actual no-sign is shown and the work zone area is officially terminated. Work zone 3 is a more straightforward work zone since the on-ramp is situated just before the advance warning area. This results in a decreased length of the work zone from 4.6km in Maarsbergen to 3.6km in Veenendaal-west. Immediately after the start of the advance warning area at 90.7hm the 90-90 signal and the PCMS are shown. On the next MTM signal, the transition area is announced with the 90-↙ signal. The following MTM signal indicates the start of the activity area and the closed right lane 'r3' with the 70-X signal. The crash barrier which is lowered is situated around the 88,0 MTM portal. At the next portal, the work zone can already be terminated with ⃠-⃠.

Table 5.6: Work zone lay-out of Maarsbergen: Work zone 1 and 2

Detector (hm)	Speed limit	MTM Signal	Local discontinuities
79,8	130	-	
79,1	90	90-90	
78,8	90	-	
78,4	90	90-↙	
77,8	70	70-X	Cones & action car
77,2	70	70-X	On-ramp
76,7	70	70-X	Cones & action car
76,4	70	-	Cones
75,8	70	70-X	Cones
75,4	70	-	
74,9	130	⃠-⃠	
74,5	130	-	

Table 5.7: Work zone lay-out of Veenendaal-west: Work zone 3

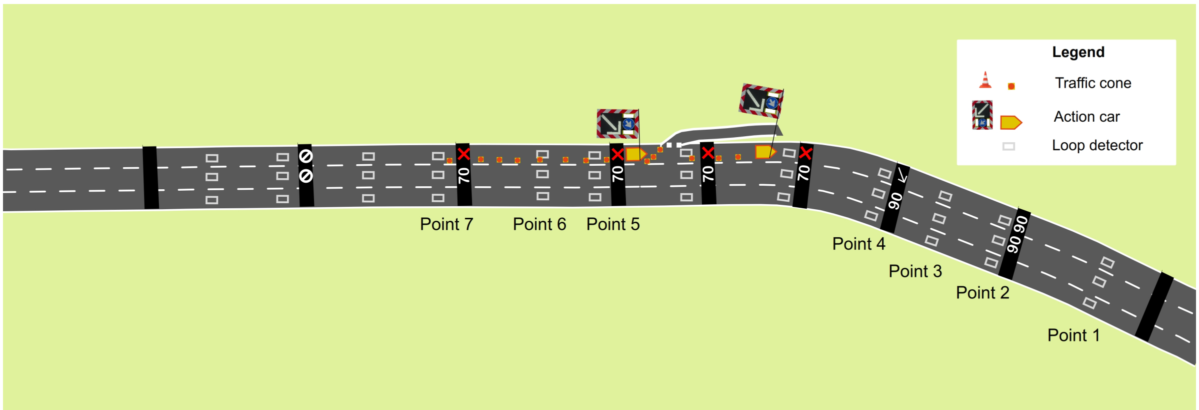
Detector (hm)	Speed limit	MTM Signal 1	MTM Signal 2	Local discontinuities
91,4	130	-	-	
91,1	130	-	-	On-ramp
90,7	90	90-90	90-90	PCMS
90,3	90	-	-	
89,8	90	90-↙	90-↙	
89,4	90	-	-	
88,9	70	70-X	90-X	Cones & action car
88,5	70	-	-	Cones
88,0	70	70-X	90-X	Cones
87,5	70	-	-	Cones
87,1	130	⃠-⃠	⃠-⃠	
86,7	130	-	-	

Although both work zones have a different layout, the work zones should be compared and this is shown in Table 5.8. The first area which can be compared is the area just before the announcement of the work zone and is numbered point 1. Also, the first signal showing a decreased speed limit of 90-90 can be easily compared. This is also the location of the PCMS, so it is of particular importance. It is numbered point 2. Then the next loop detectors without an MTM portal can be laid over each other and enumerated point 3. At point 4 the transition area announcement of 90-↙ does not give comparison complications. From this detector, the on-ramp in Maarsbergen forms a problem. Only after this on-ramp, the start of the activity area at 76.7hm can be compared with the start of the activity area in Veenendaal at 88.9hm. In work zone 1 and 2 there is a road stretch of 1.7km, with the on-ramp in between those two points. In work zone 3 only one detector without an MTM portal is left out, so 0.9 km road is excluded. From the start of the activity area in point 5, the work zone area is comparable until point 75,8 and 88,0. A strange termination situation appears in Maarsbergen where the MTM system is inconsistent with the traffic measures. From the MTM signal 70-X on 75,8 the traffic cones stop, so the activity are stopped although the red cross of the MTM system is still active. The termination symbols follow at 74,9. At 75.8hm, the traffic cones and activity stop while the red cross of the MTM system is still active. These traffic measure create an incomparable termination area.

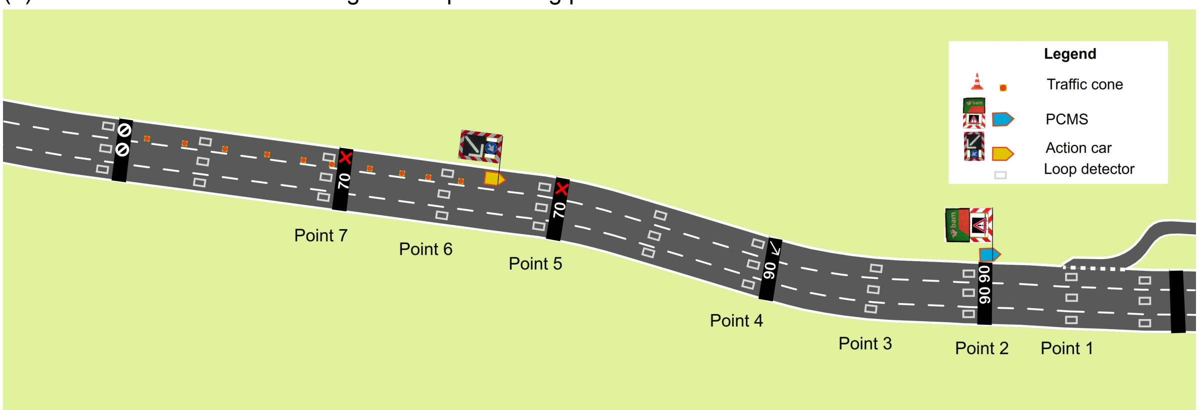
Table 5.8: Spatial comparison of work zones

Point	MTM	Speed limit	WZ 1&2 (hm)	WZ 3 (hm)	Area	Meassure
1	-	130	79,8	91,1		
2	90-90	90	79,1	90,7	Advance warning area	PCMS
3	-	90	78,8	90,3	Advance warning area	
4	90-↙	90	78,4	89,8	Transition area	
5	70-X	70	76,7	88,9	Activity area	Action car
6	-	70	76,4	88,5	Activity area	Cones
7	70-X	70	75,8	88,0	Activity area	Cones

As shown in Table 5.8, 7 points can be spatially compared according to the MTM layout, work zone layout and the function of the area in which the detector is situated. Figure 5.4 provides an overview of of the location of these points.



(a) Work zone 1 and 2 Maarsbergen data processing points



(b) Work zone 3 Veenendaal-west data processing points

Figure 5.4: Overview of loop detector locations which are used in data process and evaluation

One major spatial factor is left out in this comparison, what if the road layout like the curvature and on-ramps influences the measurements at the detector points as well? These influences are highly likely and the relation is already shown in the fish-bone Figure 3.1. The comparison should be tested regarding road consistency in a situation with no work zone, which is done in 6.3. For this comparison a statistical test is needed, this is explained in Section 5.7.1.

5.7. Statistical analysis

"In quantitative research we try to make better sense of the world through the numbers we obtain. These numbers are summarized and interpreted using statistics. Statistical methods are computational procedures that enable researchers to find patterns and meaning in numerical data [Leedy and Ellis Ormond, 2013]."

In this thesis two statistical methods are used, the Mann-whitney U test and the multiple linear regression model.

5.7.1. Mann-Whitney U test

To test if the data sets are statistically equal or different the Mann-Whitney U test can be used. The test of H.B. Mann and D.R. Whitney is a non-parametric test of the null hypothesis that it is equally likely that a randomly selected value from one sample will be less than or greater than a randomly selected value from a second sample [Mann and Whitney, 1947]. The test is comparable to the t-test however the assumptions of normality and the homogeneity of variance may be violated using the Mann-Whitney U test. Also, according to Conover [1999] comparisons of the relative efficiency between the Mann-Whitney test and the two-sample t-test is never too bad. The Mann-Whitney test is the safer test to use. By combining and ordering data, the medians of both data sets are compared. At first sight, this seems of limited usefulness and one would prefer to compare data set means. However, when the distribution of the data sets is assumed symmetric, the mean is comparable with the median.

The test tests two independent, or randomly selected, samples. The assumption of independence between the data sets of Work zone 1,2 and 3 is complicated. There is a relation between the data sets in spatial and temporal terms. Work zone 1 and 2 are spatially related, yet the data sets are categorised for this relation, and the spatial relation is the relation tested. Work zone 2 and 3 are temporally related, the work zones were present in the same period. Since both work zones lay on the same road stretch between the two significant interchanges Maanderbroek and Lunetten it can be assumed a large percentage of drivers passed both work zones. The individual behaviour of driver 1 in work zone 1 and driver 1 in work zone 2 is assumed to be dependent on personal characteristics and behaviour of that individual. The loop detector speed data is minute aggregated and individual vehicle data cannot be identified. Thus independence of both data sets is assumed.

Suppose we have one sample of n_x observations $x_1, x_2, ...x_n$ in one group and one sample of m_y observations $y_1, y_2, ...y_m$ in the other group. Let $n + m = N$. Assign ranks 1 to N to all the observations from smallest to largest, without regard from which population they came from. Let $R(x_i)$ and $R(y_j)$ represent the ranks assigned to x_i and y_j for all i and j. If several values are tied, assign each the average of the ranks that would have been assigned to them had there been no ties. If a real difference between both groups exists, then the values from one sample will be clustered at one end of the entire rank order of both samples and the second sample will be clustered at the other end. If there is no difference between the data sets, then the values will be intermixed within the rank order. The null hypothesis stated in Equation 5.3 can be translated to: if the samples medians are different then each x_i has an equal chance (probability of $\frac{1}{2}$) of being greater or smaller than each y_j.

$$H_0 : P(x_i > y_j) = \frac{1}{2} \tag{5.3}$$

Most of the recent statistical packages support the Mann-Witney U test. In this research Python^{TM} is used for the data analysis. In the python programming language, the statistical package scipy.stats is available. The scipy.stats API includes the Mann-Whitney test and this calculation method is used in this research. The calculation method includes the one-tailed and two-tailed test. The alternative hypothesis following from the two-tailed and one-tailed tests are described in Equation 5.4 and 5.5 respectively.

$$H_1 : P(x_i > y_j) \neq P(x_i > y_j) \tag{5.4}$$

$$H_1 : P(x_i > y_j) > P(y_j > x_i) \tag{5.5}$$

In this research, the effect described in the speed samples is expected to be one-tailed. Especially in the road consistency test, it can not be excluded that the effect is in both directions of the relationship. That is why the two-tailed alternative hypothesis should be used. The calculation is further made by adding up all of the ranks assigned to the sample of population one, as shown in Equation 5.6.

$$U = \sum_{i=1}^{n} R(x_i) \tag{5.6}$$

For large samples(>20), U is approximately normally distributed. In that case, the standardised value z can used, which can be calculated using Equation 5.7.

$$z = \frac{U - m_U}{\sigma_U} = \frac{U - n\frac{N-1}{n}}{\sqrt{\frac{nm}{N(N-1)}\sum_{i=1}^{N} R_i^2 - \frac{nm(N-1)^2}{4(N-1)}}} \tag{5.7}$$

5.7.2. Multiple linear regression model

Multiple linear regression is a method which models the relationship between multiple explanatory variables X and a response variable Y [Verhaeghe, 2007]. The method aims for a linear fitted line which best explains the variation of the response variable Y. The method is used to quantify character and the strength of the relationship of the explanatory variables to the response variable. Each X represents a new dimension and the β_n represents the slope of a plane in a $n + 1$ multiple dimensional space. The linear line is explained in Formula 5.8. The e, the random error, represents the difference between the observed and the by the model predicted values of Y.

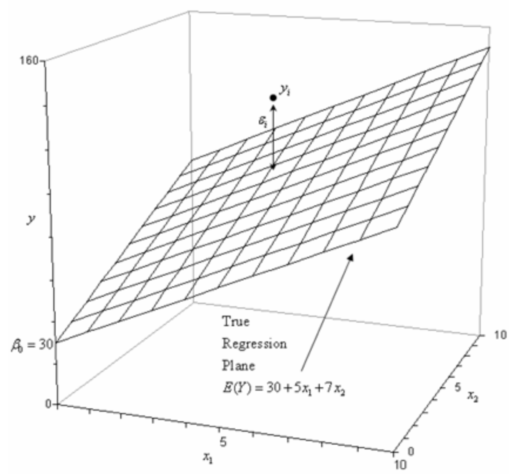


Figure 5.5: Example of a linear model with 2 X in a 3D space from: wikipedia.com

$$Y = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + ... + \beta_n X_i n + \epsilon_i \tag{5.8}$$

The line is fitted to the observed data using the least square criterion. The sum of the squared vertical deviations of all points to the line (the measuring errors e_i) should be minimal. This minimization is expressed in Equation 5.9.

$$\text{minimize} \sum \epsilon^2 = \sum (Y_i - b_0 - b_1 X_1 - b_2 X_2 - ... - b_n X_n) \tag{5.9}$$

The precision of the estimated equation can be defined by observing the variation in the response variable which can be explained through the model. This is expressed in the value R^2, which represents the proportion of variation around the mean of the response variable Y that is explained by the model.

Within the multiple regression model it is important to know if a x-variable makes a useful contribution to the overall model. To test if X_1 is a useful predictor variable the null-hypothesis 5.10 and alternative hypothesis 5.11 should be tested using the standard T-test.

$$H_0 : \beta_1 = 0 \tag{5.10}$$

$$H_1 : \beta_1 \neq 0 \tag{5.11}$$

The computations used for this test such as the b-values, R^2 and individual p-values are computed using MATLAB™. The *fitlm* function provides all these computations as well as methods to visualize and analyse the residuals. The function also provides means to find multicollinearity in the model. Multicollinearity explains if two individual explanatory variables are correlated to an extent that the model is negatively affected, causing the MLRM to become unstable. The non-existence of multicollinearity is one of the assumptions made in a MLRM which should be tested. The other assumptions of a MLRM are that: (1) the relation between the response and explanatory variables is linear, (2) the errors between observed and predicted values are normally distributed and (3) the variance around the regression line is the same for all values of the explanatory variable.

6

Data preparation

The data from the field trial will be described and prepared in this chapter. First, the conclusions from the observations will be presented in Section 6.1 since some of those observations cause data analysis difficulties. Then the data obtained with the loop detectors is decribed in Section 6.2. Then a control step is taken to check if it makes sense to compare the identified points in the Section 6.3. The set-up of the MLRM is explained in Section 6.4.

6.1. Observations of the field trial

In the night of June 20th - June 21st and night of June 21st - June 22nd two work zones were situated on the Dutch motorway A12 in the direction of Utrecht. Both sites are described in Section 5.2. In the Figure 3.1 all factors influencing speeding in work zones are defined. The factors within the research scope but outside the solution space are discussed here. The work zone activity, traffic, environmental circumstances and road operation during the field trial are described in this section.

6.1.1. Experimental sign

The experimental PCMS was placed near measuring point 90.7 which is the second point in the spatial comparison. The PCMS was placed after on-ramp Veenendaal-west and next to the MTM portal. During the field trial, the PCMS showed four different texts: 'Plaatsen afzetting', 'Momenteel geen werk', 'Werk aan vangrail' and 'Verwijderen afzetting'. An indication of the image on the PCMS can be found in Figure 4.9. In reality, the road image was as shown in Figure 6.1. In these images the PCMS is not exactly readable, this is due to the type of image and the speed of the car while driving by the PCMS.

(a) Dashcam image of sign in WZ3: No work Wednesday 21th at.

(b) Dashcam image of sign in WZ3: Work on crash barrier Wednesday 21st at.

Figure 6.1: Dashcam images of PCMS in work zone 3

6.1.2. Activity description

In both work zones sites in Maarbergen and Veenendaal, the safety barrier was lowered. For site Maarsbergen (work zone 1 and 2) this was two nights of work, while only one night was needed for Veenendaal (work zone 3). The first night of work zone 1, the heaviest equipment was used in the work zone. Figure 6.2a shows the machines in work zone 1: an excavator, a tipper truck, a truck loader crane and some smaller vehicles. Figure 6.2b shows a truck loader crane and some more modest vehicles in work zone 2. From the observations of the researcher, it can be concluded that in the two nights approximately the same equipment was present in the work zones.

(a) Dashcam image of work zone 1 June 20th

(b) Dashcam image of work zone June 21st

Figure 6.2: Dashcam images of work equipment in both work zones

6.1.3. Enforcement

From the observations [Appendix C.4;C.5] it can be concluded the police enforcement was severe in both work zone 1 and 2, while in work zone 3 no police vehicles were observed. In work zone 2, a police car was parked in the activity area for half an hour, this is called static enforcement in Table 6.1. Dynamic enforcement is a police car passing by in the work zone.

Table 6.1: Enforcement observations during field trial

Work zone	Enforcement type	Begin time	End time
1	dynamic	21:30	21:34
1	dynamic	22:00	22:04
2	static	20:00	20:30
2	dynamic	02:28	02:32

6.1.4. Environment and weather

Rain and bad weather influence speeding behaviour of traffic participants. The weather during the field trial was good, as there was no rain or heavy wind. The days were consecutive and sunset was at the same time, 22:06. A summary of the environmental circumstances can be found in Table 6.2.

Table 6.2: Overview of environmental and weather factors during the field trial (Source: history of KNMI station 'de Bilt')

Factor	Night 1	Night 2
Begin date	20-6-2017	21-6-2017
Sunset	22:06	22:06
Minimum day temperature of end day	13°C	17°C
Rain	0.0mm	0.0mm

6.1.5. Road operation

The field trial work zones were operated from the traffic management centre of Rijkswaterstaat in Utrecht. In both nights the researcher was also present in this operation centre. Due to the workable hours scheduled by RWS, the operation of the roads is a busy task between 20:00 and 22:00. Construction foreman call to apply for the start of the work zone. The total process of a normal work zone night and the field trial work zone can be found in Figures 4.3 and 4.6 respectively. After 22:00 the road operation was less labour-intensive. The work zones were monitored by the researcher on night one from 20:00 to 22:45 and on night two constantly. In night 2 in the experiment work zone 3 at 04:08 a car was spotted on the emergency lane just before the PCMS driving backwards[Appendix C.6]. At this moment the duty road operator took over the monitors. The car driving in the wrong direction drove backwards on the on-ramp and turned on the on-ramp to continue his way towards the traffic light above the exit Veenendaal-west. Although this is a serious traffic violation, luckily no incident happened.

6.1.6. Conclusion

During the field trial is was not possible to control the so-called operating environment. Several experiment control risks described in Section 4.6.2 and Appendix C.2 appeared during the trial. These risks influence the comparability of the work zones. The activity and weather circumstances in all three the work zones is comparable. The operation of both the road and the PCMS did not lead to any large deviations. Enforcement is a factor which influences speeding behaviour and was seen in work zone 1 and 2, this should be included in the data analysis.

6.2. Data description

The data preparation methods are explained in Section 5.5. The data will be filtered, enriched and categorised based on the data of the MONiCa detectors, the vehicle category detectors, the SPIN database and the observations. The speed limit was not yet present in the data sheets and is added to the data in the data preparation phase. The speed limit script is based on the SPIN database layout and operational times.

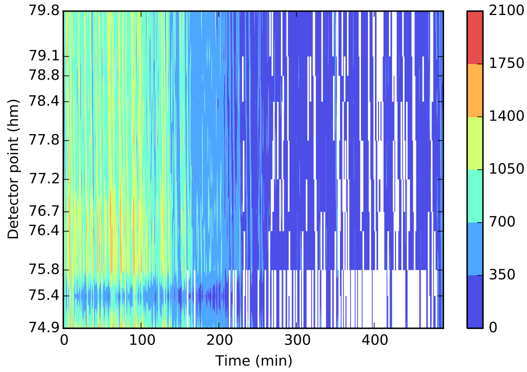
6.2.1. Loop detectors

An analysis of the flow contour plot in work zone 1 is shown in Figure 6.3. In Figure 6.3a the loop detector at 75.4hm shows a different flow contour than the other detectors in this work zone. This difference is due to the combination of temporary traffic measures and the MTM system. At this location the right lane is officially closed, so the MTM system does not measure the traffic in this lane. Because the cones and traffic measures already stopped, part of the traffic already uses the right hand lane which results in lost vehicles in the flow profile. The second work zone (same spatial profile) shows the same characteristics.

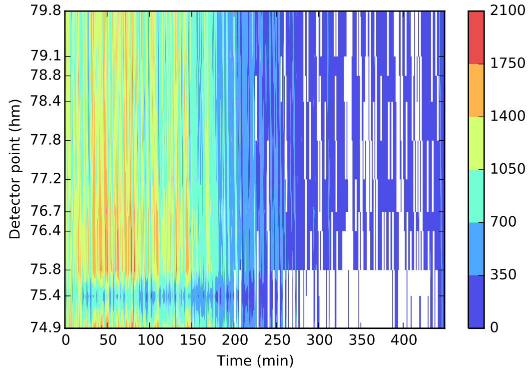
The flow profile of work zone 3, with the test sign, gives a normal flow profile as shown in Figure 6.3c. Comparing the three work zones, it seems work zone 2 was the busiest work zone. Downstream of the on-ramp in the early hours, a lot of 'red' is shown which corresponds to a higher flow.

6.2.2. Vehicle types

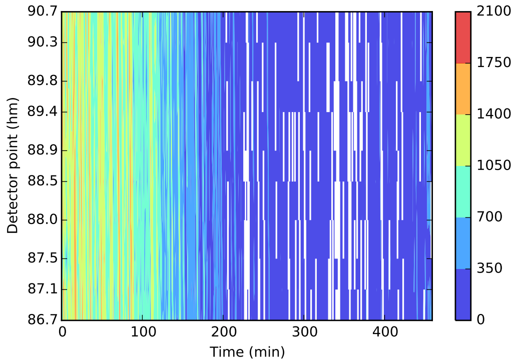
The work zones each had two loop detectors which can measure vehicle categories. In work zone 1 and 2, loop detectors at 76.7hm and 77.8hm were capable of capturing vehicle length. In work zone 3, the loop detectors on 90.7hm and 91.4hm were equipped for this purpose. In Figure 6.4, the vehicle distribution is shown for each work zone and detector. The first bar for the work zone is the detector upstream of the on-ramp (77.8hm and 91.4hm) and the second bar represents the downstream detector. In all cases, especially in work zone 1 between 02:00-02:59, the measurements of the upstream and downstream detector are comparable. Although there are small deviations which could be caused by merging vehicles, there is also the possibility these differences are caused by the margin of error of the loop detector.



(a) Flow contour of work zone 1 on Tuesday 20-06-2017 20:10 - Wednesday 22-06-2017 04:20



(b) Flow contour of work zone 2 on Wednesday 21-06-2017 20:00 - Thursday 22-06-2017 03:30



(c) Flow contour of work zone 3 on Wednesday 21-06-2017 20:50 - Thursday 22-06-2017 04:30

Figure 6.3: Flow contour plots work zones

The truck-shares in work zone 2 and 3 are comparable. That is a logical consequence of the time and location of the work zones. The work zones were present on the same night on the same road without major interchanges in between. The truck share in work zone 3 is systematically higher than the truck share in work zone 2. At 02h, the most substantial difference between work zone 2 and 3 is found (longest vehicle category: 22% vs. 25%).

Between work zone 1 and 2 larger differences can be found. Although these are situated on the same road stretch, the first work zone was present on the night of June 20th-21st of June and the second work zone was on the night of June 21st-22nd. This difference seems to create significant vehicle type differences in both directions. Early in the night the truck share is lower in work zone 1, while later the truck share is higher. The significance of this difference on the vehicle speeds is established in Section 6.3.2, where work zone 1 and 2 will be compared.

6.2.3. Flow categories

The flow categories account for different speeding behaviour in different traffic flow circumstances. The method of categorisation is explained in Section 5.5.3. The number of measurements of each flow category is both spatial and temporal dependent. The second effect becomes already clear in Figure 6.5. The heavy flow category of >600 vehicles per hour, category 1, is only measured in the first hours of the work zone. After midnight, measurements falling into this category are rarely registered. During the night fewer measurements fall in the middle category between 300 and 540 vehicles per hour and more measurements are included in the third and fourth flow categories. The patterns in Figure 6.5a (work zone 1) and Figure 6.5b (work zone 3) are comparable while the measurements were done on different nights. Work zone 1 experiences heavier traffic than work zone 3.

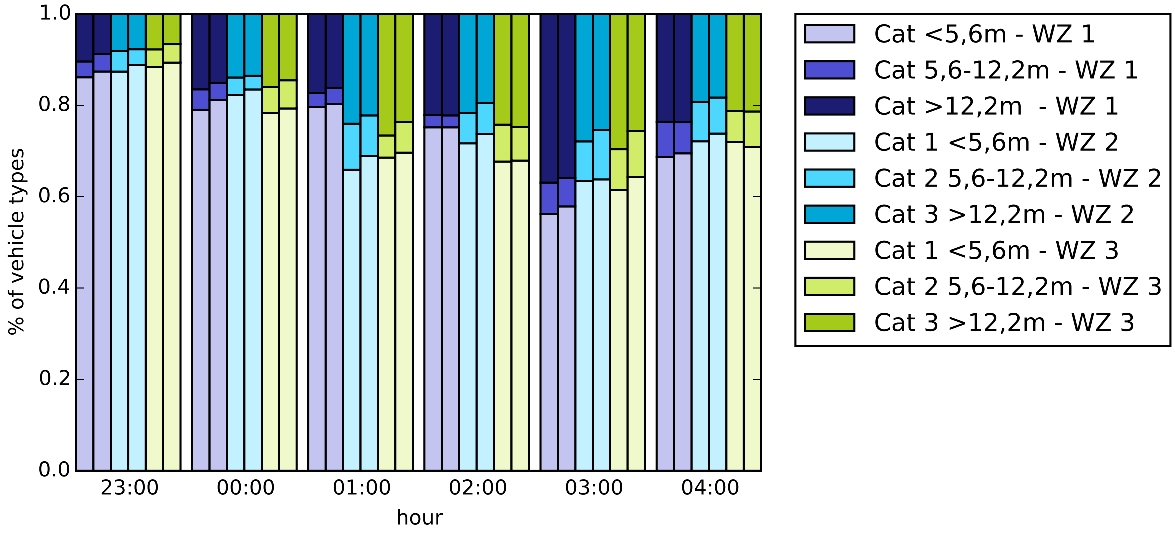
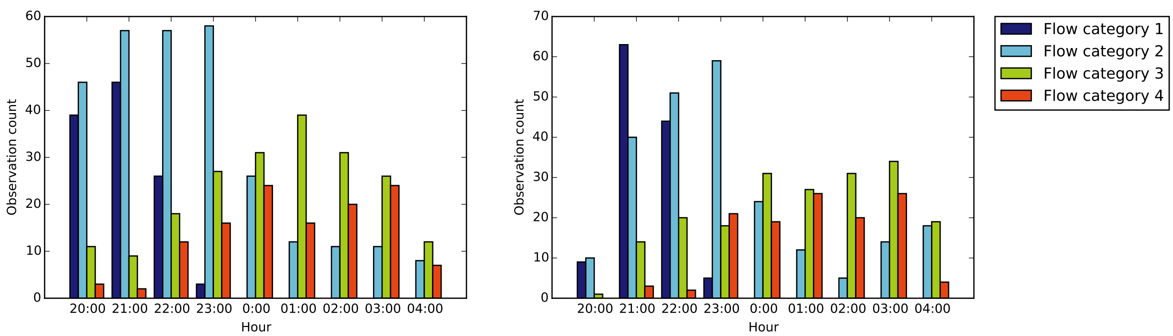


Figure 6.4: Vehicle category distribution per hour in work zones 1,2 and 3

At the detector point used in Figure 6.5, two lanes were open so every minute two measurements could be included in the count. Figure 6.6 shows the number of observations for each flow category at detector 6, which is in the activity area of the work zone and thus only has one open lane. The number of measurements in the higher flow categories increase and in the early evening there are no measurements in the third and fourth category.

In Figures 6.6a and 6.6b, it can be observed that the flow in work zone 2 is higher than in work zone 3. From 21h, the graphs are comparable because of the start time of the work zones. Work zone 3 only has 10 minutes in the 20:00 category, since the work zone started at 20:50. From 21h on the first flow category is higher in work zone 2 than work zone 3. The other flow categories show approximately the same pattern.

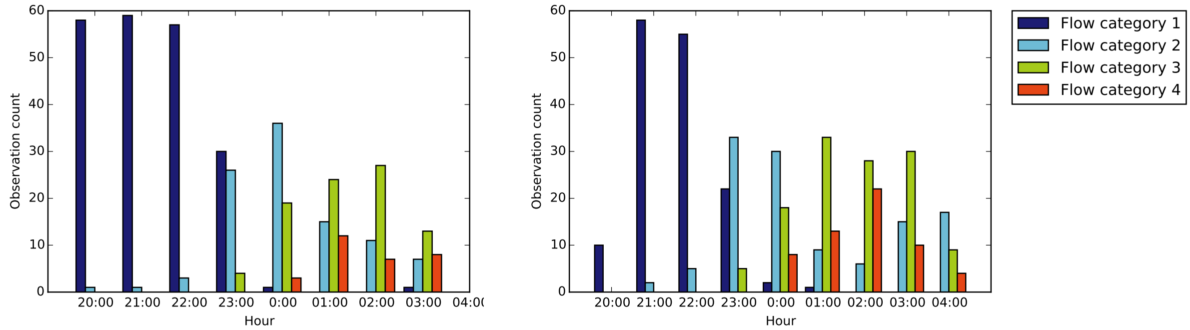
Figure 6.7 shows the median speed through work zones 2 and 3. From the different flow categories it can be concluded that the fundamental relationship holds at least outside the work zone in point 1. The lowest flow categories have the largest speed median. In work zone 2, the relation also holds for the most part. The exception is point 5, where the on-ramp still has an influence. Here the flow categories mix and the median speed is approximately the same for categories 2, 3 and 4. A speed increase is



(a) Number of observations in work zone 1 detector 2

(b) Number of observations in work zone 3 detector 2

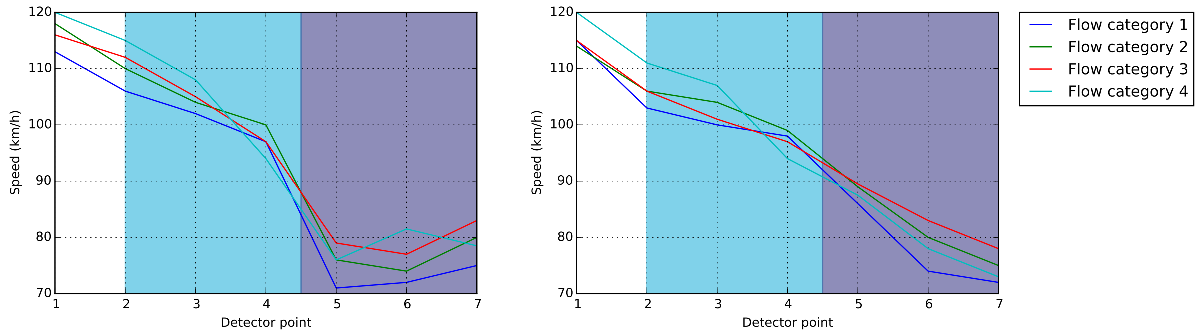
Figure 6.5: Number of observations in each flow category per hour in point 2. In point 2 the PCMS is located and it is part of the advance warning area



(a) Number of observations in work zone 2 detector 6

(b) Number of observations in work zone 3 detector 6

Figure 6.6: Number of observations in each flow category per hour in point 6. Point 6 is situated in the activity area.



(a) Median speed per flow category work zone 2

(b) Median speed per flow category work zone 3

Figure 6.7: Median speed in each flow category per point in the work zone

shown from the on-ramp on through the activity area of work zone 2. In work zone 3 an unexpected effect is shown, the lower flow vehicles have lower speed than the vehicles in the higher flow category 2. The traffic seems to meet its maximum capacity and has the lowest speed.

From the perspective of the field trial, the categories with the lowest flow (category 3 and 4) are most interesting. In the categories with higher flow, the drivers are influenced by each other's behaviour. In flow category 1 the traffic seems to meet its maximal capacity. This can be seen in the speed contour plot of Figure D.8 early in the night, and the speed drop and increase in Figure 6.7a. The speed drop and increase is not explainable by the work zone alone and indicates a typical traffic jam.

6.2.4. Conclusion

Based on the data description we can conclude the loop detectors function. There is a definite speed and flow profile through time and space. The vehicle length detectors show significant different vehicle types in space and time. The vehicle detectors in the same work zone show fluctuations and the work zones have different vehicle type numbers as well. The speed differs in each flow category. By combining the flow and truck share different speed patterns could be created, so this effect should be investigated. This can be researched by comparing work zone 1 and 2 since they are spatially the same.

6.3. Comparison of sites

Because of the differences between the work zones in time and space, these effects should be researched. Are there spatial components which influence speed such that the work zones are not comparable? Those factors are tested in the road consistency test. Another question following from the approach is: are there temporal components which influence the speed such that the work zones are not comparable? These temporal components are researched using work zones 1 and 2 which are spatially comparable and were on the road in different nights. The points are individually compared using the Mann-Whitney U test.

6.3.1. Road consistency

For the road consistency test the work zone spatial comparison is used which is explained in Section 5.6.2. The work zones are compared based on their MTM signage and the on-ramp in work zones 1 and 2 is excluded as much as possible. Seven points remain which will be tested in a non-work zone situation. In this manner, other spacial factors influencing the speed measurements can be found. The objective of the road consistency test is to find if it is indeed valid to compare the individual points by non-work zone speed measurements. The night of June 20th is tested from 00:00-04:30. In this data set, no measurements can be found in vehicle category 1 (high flow). Two other nights of speed measurements are added to the comparison, the night of May 3-4 and the night of May 25-26. In these nights the data from 21:00-04:30 is analysed.

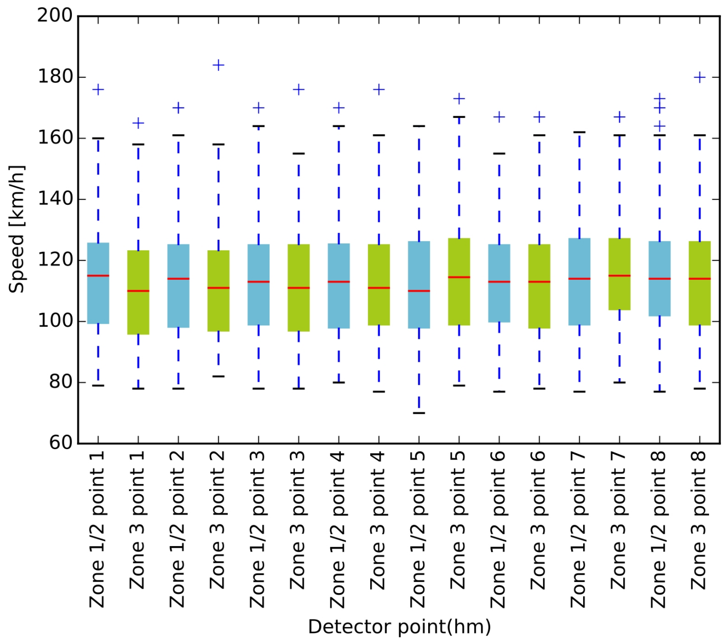


Figure 6.8: Speed distribution in non work zone situation vehicle category 3

Looking at Figure 6.8 one sees that in the third vehicle category the speeds on a regular night are indeed comparable. At point 5 near the on-ramp in Maarsbergen, the most substantial speed median difference is found. In Veenendaal, represented by zone 3, the speed at point 5 is systematically higher in all categories. This effect can also be observed near point 1, where the speed in Veenendaal seems to be consistently lower than in Maarsbergen. This can also be explained by the location of the on-ramp at this measuring point. Its impact is smaller than that of the on-ramp in Maarsbergen, where the result is still visible one point downstream. The impact of on-ramp Veenendaal is not noticeable downstream of the detector.

The two-tailed Mann Whitney U-test is used to test if the speed distribution of the points per flow category is statistically from the same distribution. The two-tailed test ensures the relationship will be tested in both directions (lower and higher). The speed distributions from Maarsbergen (work zone 1 and 2) and Veenendaal (work zone 3) are tested per point per flow category. The p-values of all the tests can be found in Tables D.7, D.8 and D.9. A summary is provided in Table 6.3. If a test scored between 0.1 and 0.05 a 0 was added and if a test was below 0.05 a minus was added. Two minuses mean that the test failed twice, while a plus means that the test scored higher than 0.1 in all cases.

Table 6.3: Road consistency test per flow category summary of 3-4may, 24-25 may and 20 may from 21:00-04:30

Point	flow category 1	Flow category 2	Flow category 3	Flow category 4
1	-	-	0	0
2	-	+	+	+
3	+	+	+	+
4	+	-	0	0
5	- -	- -	0 0	0
6	+	+	-	+
7	+	+	+	+

From the road consistency summary in Table 6.3, it can be concluded that in the high flow categories the zones are not comparable. Especially around the on-ramp of Maarsbergen, the inconsistency shows by two failed tests at point 5. Also in the low flow category 3, the test fails at point 6. In flow category 4, most points pass the road consistency test. Around point 4 in the night of May 24/25, the p-value of the test is 0.072 which is low. The test of point 5 on the night of June 20th gives a low result of 0.068. Point 1 almost fails the test with a score of 0.05002 on the night of May 3/4.

Testing three different days for road consistency gives a good certainty there are no significant differences regarding road layout which influence the 4th flow category of vehicles.

6.3.2. Work zone comparison

The normal work zone situation is not interfered with in work zone 1 and 2. Since they are spatially exactly identical, except for a difference in flow and truck shares, no other temporal effects are expected. When categorising the flow, no differences are expected at all. Work zone 1 and 2 should have the same speed distribution in both nights. If this is not the case, then an yet unknown factor affects the work zones.

Figure 6.9 shows the result of the speed comparison of flow category 1 of work zone 1 and 2. The result is comparable to flow category 2. At point 6 a speed median difference is visible, the speed in work zone 2 is lower than that in work zone 1. Because of the speed variation in this flow category, and especially at this point in the activity area, the difference is more substantial than it looks when comparing the medians in absolute terms.

The distribution of vehicle category 3 of work zone 1 and 2 is shown in Figure 6.10. In this flow category a difference of speed medians is shown at point 1. In flow-category 4 this difference disappears. In the low flow categories, the speed distributions of work zone 1 and work zone 2 are comparable. To test if the differences shown in the box plot are statistically relevant, the Mann-Whitney U test is conducted.

Table 6.4 shows the Mann-Whitney U-test p-value. The alternative hypothesis tested is that the speed distribution at a certain detector for a certain flow category is different for work zone 1 and 2. The test is two-tailed, so it tests for both positive and negative differences. With a significance level of 95%, the test shows that flow categories 1 and 2 at point 6 show significantly different speed distributions. In flow-category 3 and 4 no significant differences can be found, although point 1 in category 3 almost fails the test with a score of 0.052 (< 0.05 would mean a statistically significant different speed distribution).

The vehicle categories could be a temporal effect influencing the speed consistency of work zone 1 and 2. There is a difference in vehicle types between work zone 1 and 2 which is explained in Section 6.2.2. The other possible factor influencing this variation is an effect of the repeated work zone. Work zone 2 is the second work zone drivers encounter between the interchanges Maanderbroek and Lunetten. The last possible effect is a small, developing traffic jam, in which case the flow and especially

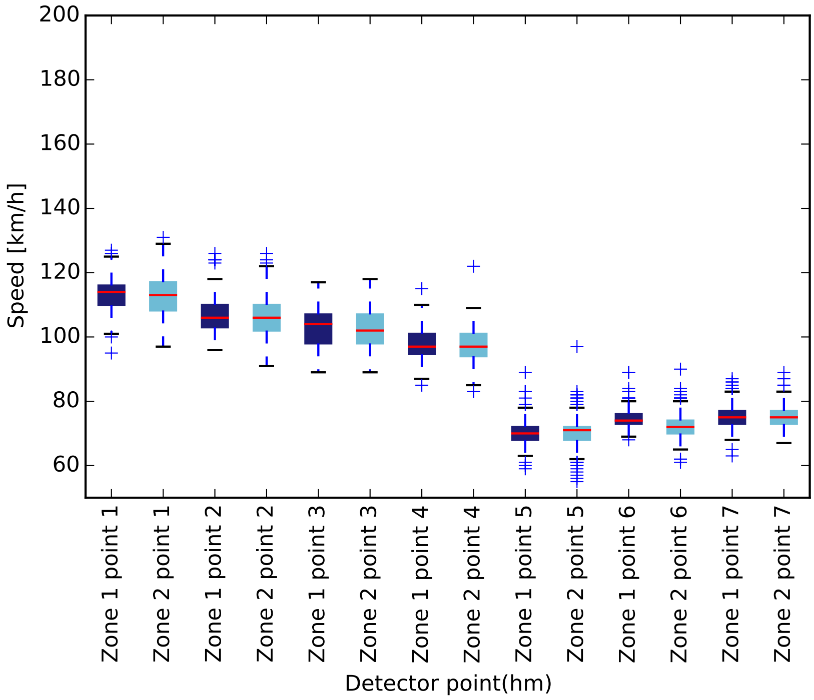


Figure 6.9: Speed distribution of flow category 1 in work zone 1 and 2

Table 6.4: P-value result of two-tailed Mann-Whitney U test per point per flow category of work zone 1 and work zone 2

Point	Flow category 1	Flow category 2	Flow category 3	Flow category 4
1	0.49	0.49	0.05	0.29
2	0.78	0.82	0.84	0.37
3	0.62	0.29	0.65	0.73
4	0.22	0.65	0.74	0.21
5	0.67	0.02	0.26	0.91
6	0.00	0.01	0.91	0.81
7	0.65	0.37	0.91	0.29

the speed drops. We know from the flow contour plots in figure 6.3 that WZ 2 was busier than WZ 3. This would indeed be most visible in the high flow categories. It is impossible to determine which of the three identified causes is most probable or most significant using this method.

6.3.3. Conclusions

Based on the road consistency analysis using the Mann-Whitney U test and individual points, it can be concluded that especially during high flow the points can not be compared one on one. Around the on-ramps, at the beginning of work zone 3 and the middle of work zone 1 and 2, the differences are significant. Comparing work zone 1 and 2 should identify temporal differences since both work zones were situated in Maarsbergen. Again during higher flows, differences show.

Using the Mann-Whitney U test to identify and name the cause of speed differences is hard since the road lay-out (spatial) and flow (temporal) differences are large. This analysis is performed, leading to inconclusive results which can be found in Appendix D. A multiple linear regression model is chosen to further evaluate the impact of the PCMS. In this model the spatial and temporal components can be included and their effect, the direction of the effect and the significance can be found. To research

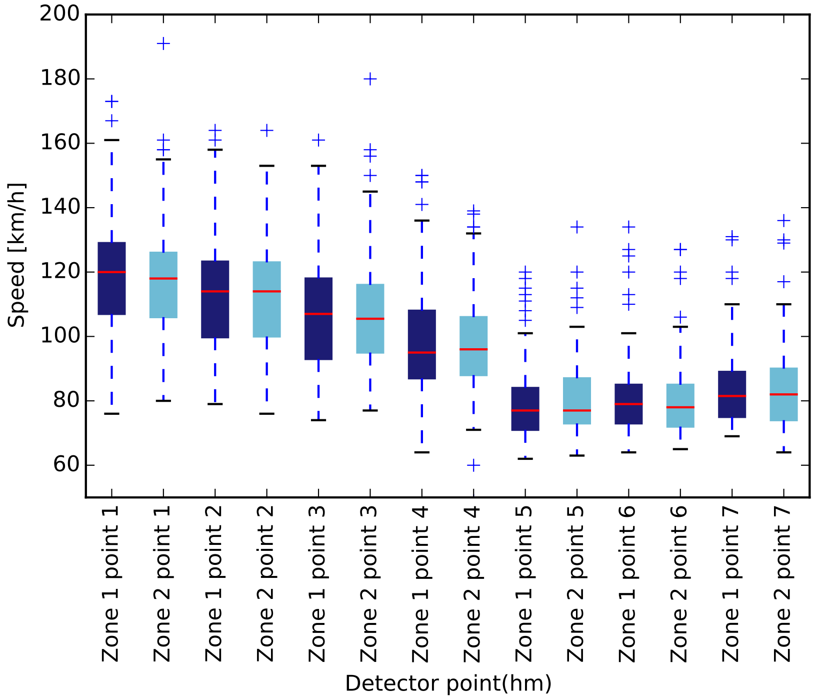


Figure 6.10: Speed distribution of vehicle category 3 in work zone 1 and 2

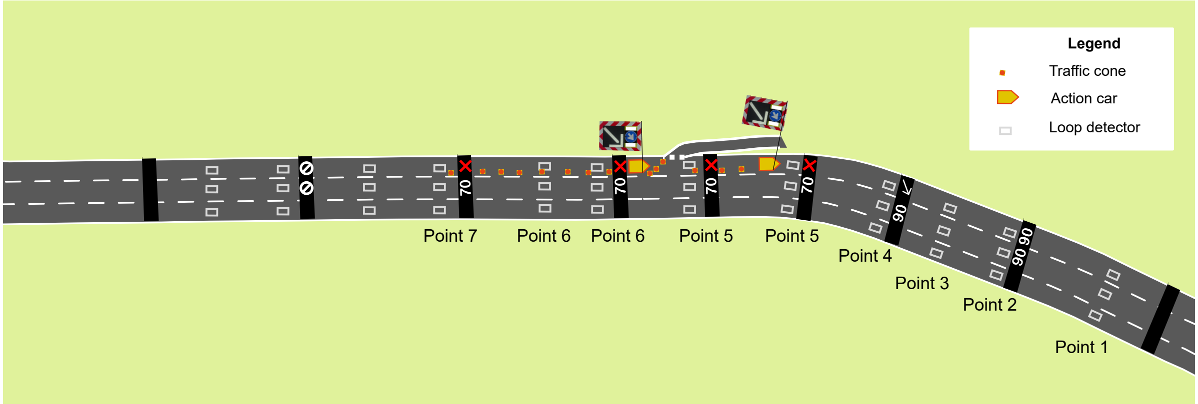
the effect of the dynamic speed limit in terms of speed limit compliance the linear regression model is unsuited since the duration of the dynamic speed limit is limited. The time period with the 90 km/h speed limit (phase 2) is compared to the 70 km/h speed limit (phase 3), for the same flow category and work zone.

6.4. Model set-up

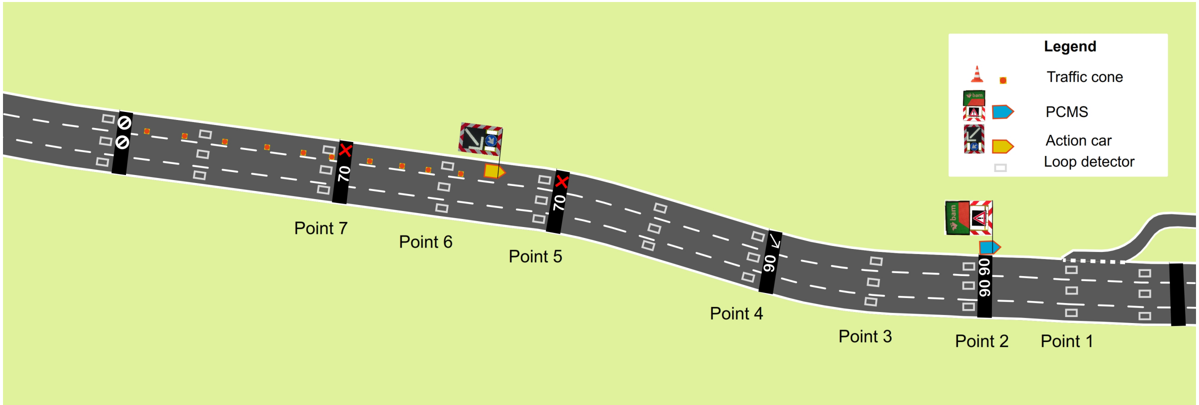
From the observations it can be concluded enforcement is a factor which should be included in the model. From the data description in Section 6.2 and the work zone comparison in Section 6.3.2, the flow and truck share are shown to influence the speed as well. From the road consistency test in Section 6.3.1 we have seen that the on-ramp is Maarsbergen (work zone 1 and 2) has a large influence in the non-work zone situation. The on-ramp in Veenendaal has less effect yet in the high flow categories points 1 and 2 (91.1 hm and 90.7 hm) the speed is influenced. Another spatial factor is the curvature of the road, since in the road consistency test the curvature does not stand out the chance that it has a significant influence is not large, it it therefore excluded from the model. From literature and the fishbone diagram in Figure 3.1, it is known that whether or not there is activity in the work zone influences the drivers' speed. The last variable added in the model is the PCMS itself, of which both the effect and the length of the effect are unknown.

$$Y_i = b_0 - b_1X_1 - b_2X_2 - ... - b_nX_n \tag{6.1}$$

Speed is the predicted variable. Each minute aggregated speed measurements in 3 work zones, on the 7 points, in each lane is listed in the model database. The linear model accounts for the spatial profile of the work zone by using a categorical variable. This variable is based on the points described in Figure 5.4. However, since in this model the spatial effect do not have to be avoided but can be included. It is more logical to divide the points more according to their order and speed limit instead of the points with the most matching spatial factors. This leads to the new point deviation of Figure 6.11. The spatial effect in the model is created using a category variable 'Point', this is shown in Equation 6.2.



(a) Work zone 1 and 2 Maarsbergen MLRM data points



(b) Work zone 3 Veenendaal-west MLRM data points

Figure 6.11: Overview of loop detector locations which are used in the MLRM

$$
\begin{aligned}
Y_i = b_{0_{point1}} + b_1 X_{flow} + b_2 X_{truck\%} + b_3 X_{enforce} + b_4 X_{PCMS} + b_5 X_{rampM} + b_5 X_{rampV} \\
+ b_6 X_{activity} + b_{0_{point2}} + b_{0_{point3}} + b_{0_{point4}} + b_{0_{point5}} + b_{0_{point6}} + b_{0_{point7}}
\end{aligned}
\tag{6.2}
$$

6.4.1. Truck share and flow

The loop detectors collect flow and speed minute aggregated data. The flow can be used one on one together with the speed measurements. The truck share is only measured in two loop detectors in each work zone, so the rest of the points are assigned to a vehicle length loop detector. The truck, middle bus and car shares are computed using the 5-minute total flow, and compute the 5-minute aggregated category shares of the 5-minute total flow. This is done using a running mean, so each minute is the middle minute, and the surrounding measurements are used for the computation of the category shares. Both the truck share and the flow are expected to influence the speed negatively.

Since the truck share's computation is based on the flow, the truck share could be linearly predicted from the flow. If this is the case, the model contains multicollinearity and this would result in an unstable multiple linear regression model.. This relation is tested before implementation of the variables in the model. The correlation r of both variables is -0.47 with a $p - value$ of 0. Although the relation is significant, a correlation of 0.47 is not very high. A correlation of 0.8 would indicate true multicollinearity. In case of high correlation there is almost certainly multicollinearity, but the inverse is not necessarily true. For now both values are included in the model, but if the model presents itself as unstable the problem of multicollinearity should investigated further.

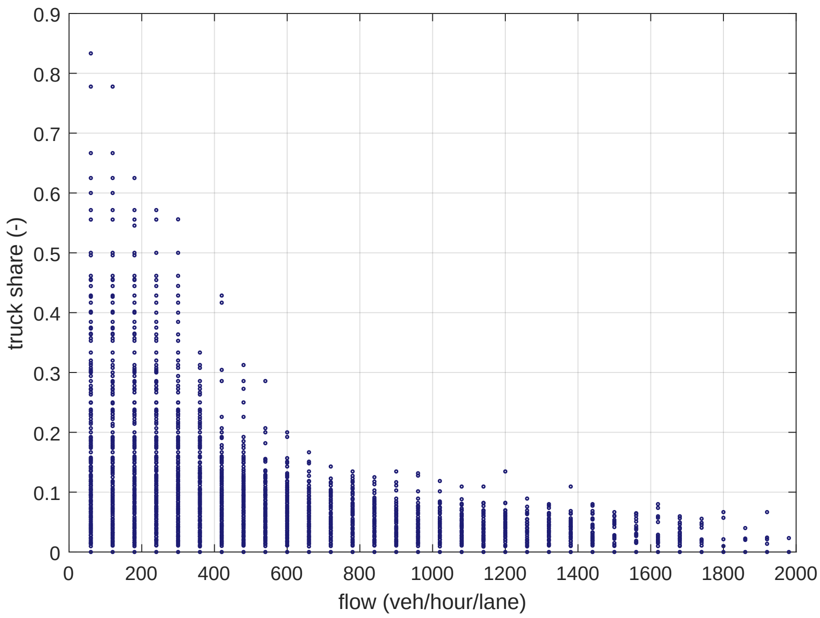


Figure 6.12: Scatter plot of relation flow and truck-share

6.4.2. Enforcement

Enforcement is a so called dummy variable in the model, it is modelled either 0 or 1. All measurements within two minutes of the observation of dynamic enforcement in a work zone will have an enforcement variable equal to 1. A special case is the static enforcement, where all the measurements in a work zone between the arrival and departure will have an enforcement variable equal to 1. The hypothesis is the enforcement will lower the speed and therefore the variable will have a negative effect.

6.4.3. On-ramps

In the road consistency test of Section 6.3.1 it is shown the on-ramp in the middle of work zone 1 and 2 has a larger effect than that of the on-ramp in the beginning of work zone 3. Since these effects are different, the on-ramps are modelled individually. They are modelled over a length of 500m upstream of the on-ramp and 800m downstream of the on-ramp. This is equal to the turbulence area of a Dutch on-ramp found by Hovenga [2014].

6.4.4. Activity

Activity is also modelled as a dummy variable, which depends mainly on the location of the observation. The activity is modelled ’1’ at 76.7 and 76.4 hm in work zone 1 and 2. In work zone 3 there was a time without activity and a higher speed limit, during this period the activity was ’0’ in all detector points. In the activity period, the activity was modelled ’1’ at 88.5 and 88.0 hm. It is expected the presence of activity will decrease the speed, this is already supported by Debnath et al. [2014] and in the early findings of Benekohal et al. [1992].

6.4.5. PCMS

The effect and the length of the effect of the PCMS are unknown. That is why the PCMS should be modelled in different ways to see which effect fits best. The possibilities are explained in Table 6.5. All possible effects are modelled as linear decay from 90.7hm, which was the location of the PCMS, to a different detector point. The standard modelling method ’PCMS’ follows this same decay over the length of work zone 3. It is hypothesised the PCMS will decrease speed and that the distance of this effect will be limited.

Table 6.5: Possible modelling methods of the PCMS

HM	PCMS	PCMS_0	PCMS_1	PCMS_2	PCMS_3	PCMS_4	PCMS_5
87.1	0	0	0	0	0	0	0
87.5	0.11	0	0	0	0	0	0
88.0	0.22	0	0	0	0	0	0
88.5	0.36	0	0	0	0	0	0.17
88.9	0.50	0	0	0	0	0.2	0.33
89.4	0.61	0	0	0	0.25	0.4	0.50
89.8	0.75	0	0	0.333	0.5	0.6	0.67
90.3	0.86	0	0.5	0.667	0.75	0.8	0.83
90.7	1	1	1	1	1	1	1
91.1	0	0	0	0	0	0	0

7

Results of the field trial

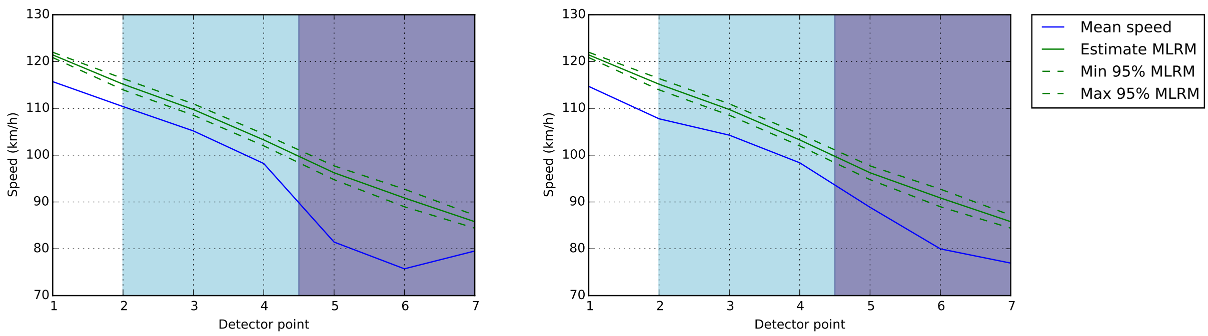
In this chapter, the results of the field trial are presented. In Section 7.1 the effect of the PCMS is evaluated using a Multiple Linear Regression Model (MLRM). The effect of the dynamic speed limit is studied in Section 7.2. The effect cannot be evaluated using the MLRM and therefore a one on one comparison is made between two different work zone phases.

7.1. Effect of PCMS

The effect of the PCMS is modelled using the MLRM described in Section 6.4. The outliers are filtered for each detector point and work zone based on the MATLAB™ default *isoutlier* filter. In this filter, an outlier is a value that is more than three scaled median absolute deviations away from the median. After filtering the outliers, 13,786 out of 14,797 (93.2%) observations remain. The model described in this section has an overall fit of R^2 0.725, an F(2.79E+3) with a p<0.001. This means that the overall model performs well, it is neither under nor over-fitted. Furthermore, the overall model is tested statistically significant. In this section, the model is explained step by step. The spatial profile is explained first, then the temporal factors (such as flow and truck share) are added and finally the spatial factors (such as on-ramps and PCMS) are added.

7.1.1. Spatial speed profile of work zones

The categorical variable 'Point' represents the standard spatial profile through the work zones. The speed profile through the work zones are presented in Figure 7.1 and the results of the MLRM are given in Table 7.1. The speed decrease from point 1 to point 7 is gradual with 5-7 km/h per point. The speed limit is shown in the colour of the background surfaces, the speed limit is 90 km/h in points 2 to



(a) Speed profile of multiple linear regression model 'points' in work zone 2

(b) Speed profile of multiple linear regression model 'points' in work zone 3

Figure 7.1: Modelled and real spatial speed profile of work zone 2 and 3

4 and 70 km/h in the points 5 to 7. With a standard road profile and traffic measures, the estimated speed is well above the speed limit. The p-values of the individual points are close to zero and the 95% confidence intervals (CI 95) have a relatively small bandwidth of +- 2 km/h.

Table 7.1: Result of categorical value 'Point' defining spatial speed profile in the work zones

	Estimate (km/h)	CI 95 min (km/h)	CI 95 max (km/h)	pValue
(Intercept)	121.42	120.85	121.98	<0.001
pointmdl_2	-6.26	-6.90	-5.62	<0.001
pointmdl_3	-11.67	-12.32	-11.02	<0.001
pointmdl_4	-18.16	-18.86	-17.46	<0.001
pointmdl_5	-25.18	-26.09	-24.27	<0.001
pointmdl_6	-30.56	-31.88	-29.25	<0.001
pointmdl_7	-35.63	-36.44	-34.82	<0.001

7.1.2. Temporal factors influencing the speed profile in the work zones

The temporal factors influencing the work zone speed are flow, truck share and enforcement. The found estimates in the model are presented in Table 7.2. As expected, the truck share and flow have negative coefficients which means they have a negative impact on the speed. Enforcement is modelled such that it has a positive impact on the speed. This is highly unlikely since we know from literature [SWOV, 2014] that police presence has a significantly large, negative effect. The unexpected outcome could be caused by the modelling method or the low number of observations but this will be elaborated on in Section 8.1.1. The P-values of all factors are below the 95% significance level, yet it is clear enforcement has a low significance compared to the flow and truck effects.

Table 7.2: Result of other spatial and temporal factors defining speed in the work zones

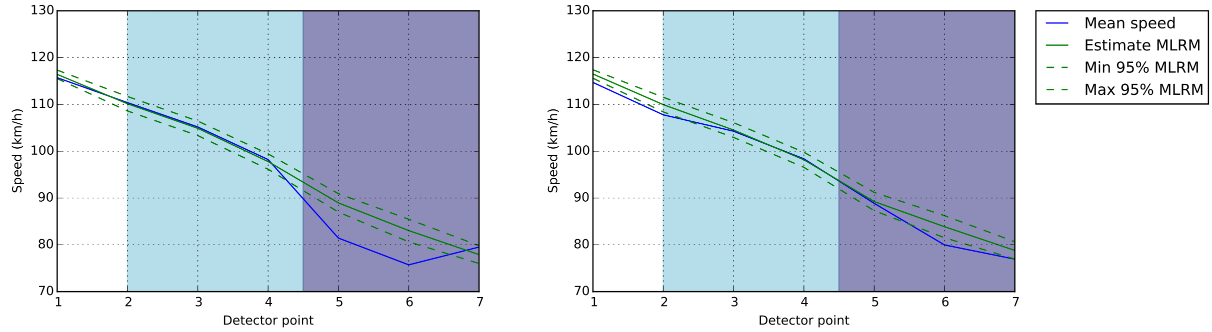
	Estimate (km/h)	CI 95 min (km/h)	CI 95 max (km/h)	pValue
Flow	-0.01	-0.01	-0.01	<0.001
Truck-share	-19.77	-21.19	-18.35	<0.001
Enforcement	0.96	0.13	1.79	2.34E-02

Figure 7.2 shows the result of the model variables 'point', 'truck share' and 'flow'. The mean flow and truck share per point per work zone are multiplied by their coefficient from the regression model. This improves the fit of the model, especially in the 90 km/h area. In the 70 km/h area, only one lane is available for traffic so the flow and truck shares increase. The negative effect of flow and truck share together with their higher values makes that the MLRM speed is lower in this area, just like the observed mean speed. Yet, the figure shows other effects influence the speed as well because the model and observed speed are still different in the 70 km/h area.

7.1.3. Spatial factors influencing the speed profile in the work zones

The spatial factors which are added to the model are: the on-ramps, activity and the PCMS. The results of the MLRM are presented in Table 7.3. The PCMS has, as hypothesized, a negative effect on the speed. The effect is small, but significant, with an estimate of -1.25 km/h. The on-ramp in Maarsbergen (work zone 1 and 2) has a large and negative effect on the speed. This could already be identified in Figure 7.2a, where a large unexplained speed drop is shown around points 4-6. By adding the on-ramp, the fit around the points shown in Figure 7.3b improves significantly.

The on-ramp in Veenendaal (work zone 3) has a smaller effect compared to the other on-ramp, but larger compared to the PCMS. It is also more significant than that of the PCMS with a p-value of 5.48E-



(a) Speed profile with flow and truck-share of multiple linear regression model in work zone 2

(b) Speed profile with flow and truck-share of multiple linear regression model in work zone 3

Figure 7.2: Modelled and real spatial speed profile of work zone 2 and 3 with flow and truck-share

08. The last substantial effect is that of activity, causing a speed decrease of -3.48 km/h when present. The activity effect relates to the fact that drivers slow down if work is being done which is visible to the driver. The fit of the overall model is presented in Figure 7.3. Earlier the R^2 of the total model was mentioned, it is 0.725.

Table 7.3: Result of other spatial and temporal factors defining speed in the work zones

	Estimate (km/h)	CI 95 min (km/h)	CI 95 max (km/h)	pValue
PCMS	-1.25	-1.90	-0.60	<0.001
Maarsbergen on-ramp	-11.89	-12.83	-10.95	<0.001
Veenendaal on-ramp	-2.27	-3.09	-1.45	<0.001
Activity	-3.48	-4.58	-2.38	<0.001

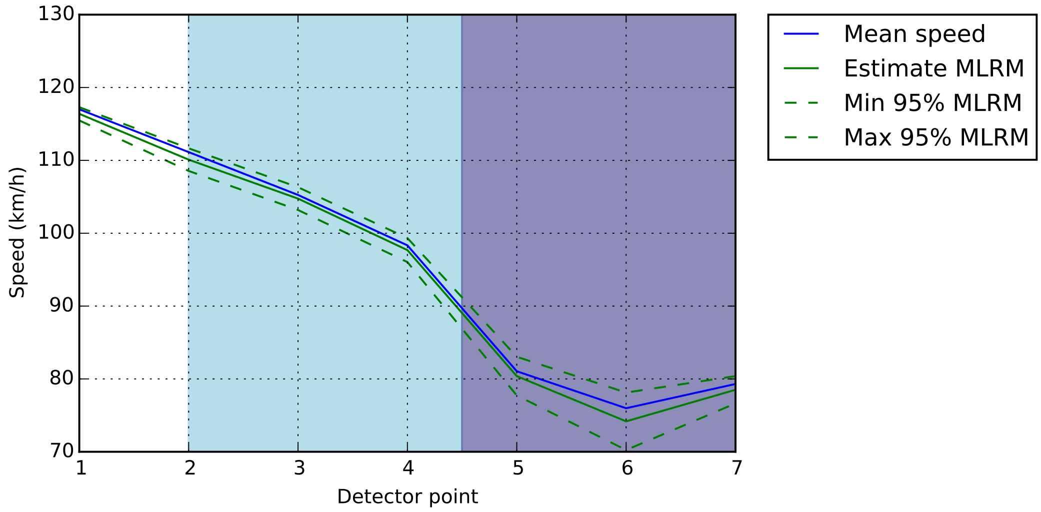
7.1.4. Length of PCMS effect

While the other factors are already tested in literature or their modelling is straightforward, for the effect of the PCMS an assumption is made. The assumption is that the PCMS has a linear decreasing effect from the location of the PCMS (point 2) until the end of the work zone. All modelling variations of the PCMS are described in Table 6.5. If the overall model performs better using one of the PCMS model variations, it is clear this variation is closer to the 'truth'.

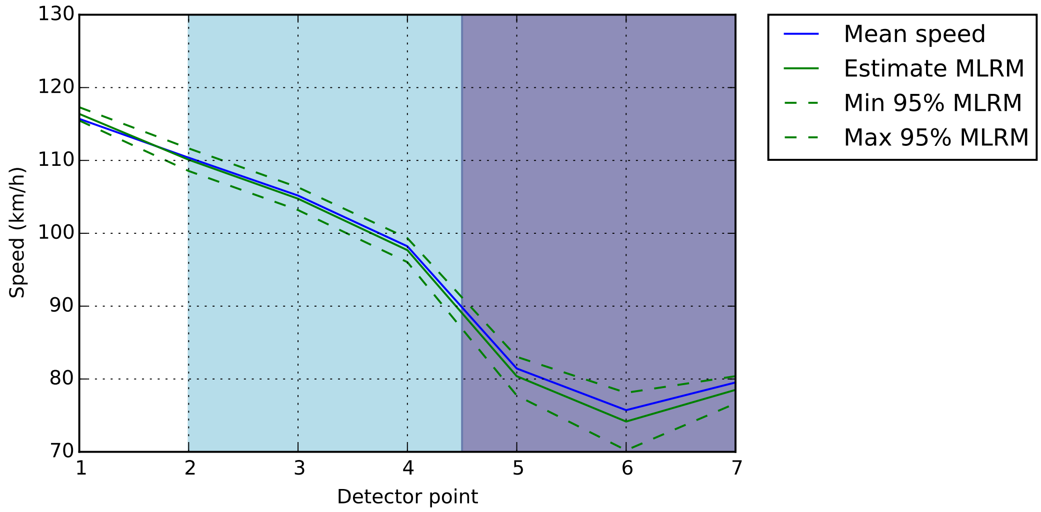
Table 7.4: MLRM outcomes with different PCMS modelling methods

Variable	estimate (km/h)	pValue	Vonramp (km/h)	pValue2	R-squared
PCMS	-1.25	1.78E-04	-2.27	5.46E-08	0.725
PCMS_0	-1.92	3.26E-04	-2.21	3.06E-07	0.725
PCMS_1	-1.61	1.41E-03	-2.17	1.82E-06	0.725
PCMS_2	-1.31	2.97E-03	-2.28	2.61E-07	0.725
PCMS_3	-1.11	5.52E-03	-2.38	4.26E-08	0.725
PCMS_4	-1.13	2.56E-03	-2.36	3.59E-08	0.725
PCMS_5	-1.24	4.98E-04	-2.28	7.14E-08	0.725

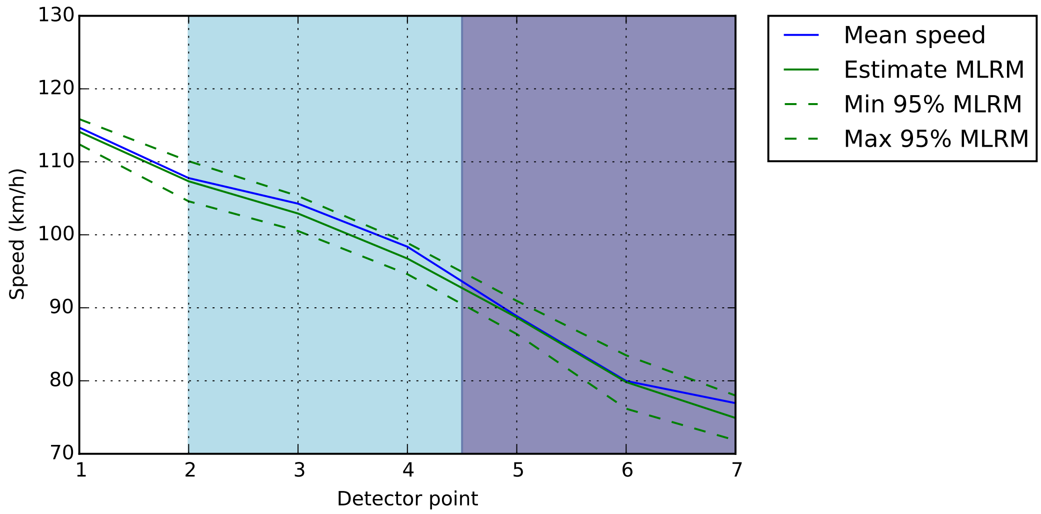
In Table 7.4 the outcomes of each alternative for modelling the PCMS is presented. For both the PCMS variable and the Veenendaal on-ramp, the coefficient estimates, the corresponding p-values and total R-squared are given. The total MLRM output can be found in Appendix E.1.



(a) Speed profile total multiple linear regression model in work zone 1



(b) Speed profile total multiple linear regression model in work zone 2



(c) Speed profile total multiple linear regression model in work zone 3

Figure 7.3: Modelled and real spatial speed profile of work zone 2 and 3 total MLRM

The outcome of the on-ramp estimate is also included because at some points the PCMS and on-ramp variables are both present. If the PCMS is only modelled at its location the effect is larger than in the standard model, -1.92 km/h instead of 1.25. If the PCMS is modelled longer than only its location, the estimate decreases and the p-value of the estimate increases. The estimate becomes less significant with the least significant p-value at 'PCMS_3'. Therefore it is more likely that the PCMS had a longer effect, as it is unlikely that the PCMS effect is limited to one location.

7.2. Effect of the dynamic speed limit

The dynamic speed limit was applied in the 'no visible activity' phase in work zone 3. According to the work phases described in Table 5.5 this is the second work zone phase, after 'placement of traffic measures' and before 'work on crash barrier'. First, it is determined which flow category should be studied to find the effect of the dynamic speed limit. In Figure 7.5a one finds the flow categories count of phase 2 of work zone 3 in each point. The phase is early in the evening, and most measurements fall in the first flow category of >600 vehicles/hour/lane. In this flow-category, the work zone is not spatially comparable with work zone 1 or 2 as is described in Section 6.3. The 90km/h phase can however be compared with the same flow category in a different work zone phase. In this case that is phase 3, which has the most observations and contains the message 'work on the barrier'. As shown in Figure 7.5b there are far more observations in this work zone phase. This is because of the length of the phase, which can be found in Table 5.5. Since the same work zone is compared, all eight points from the advance warning area until the activity area of the work zone can be included. This results in the spatial overview of Figure 7.4.

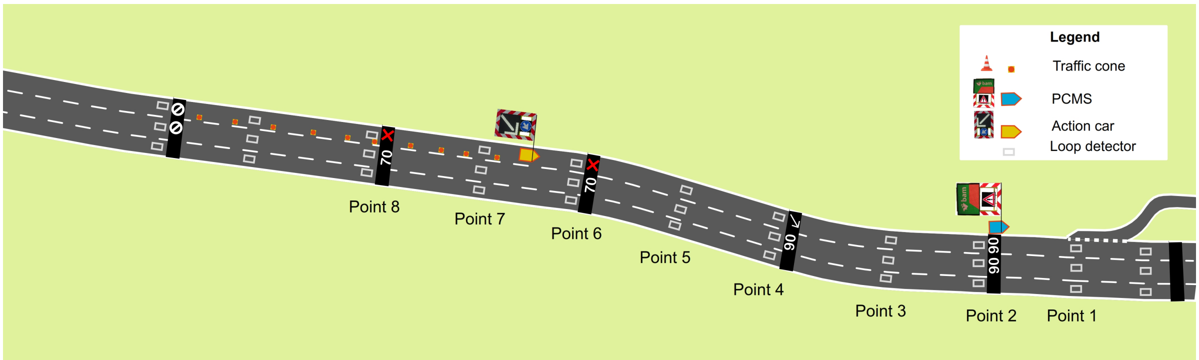
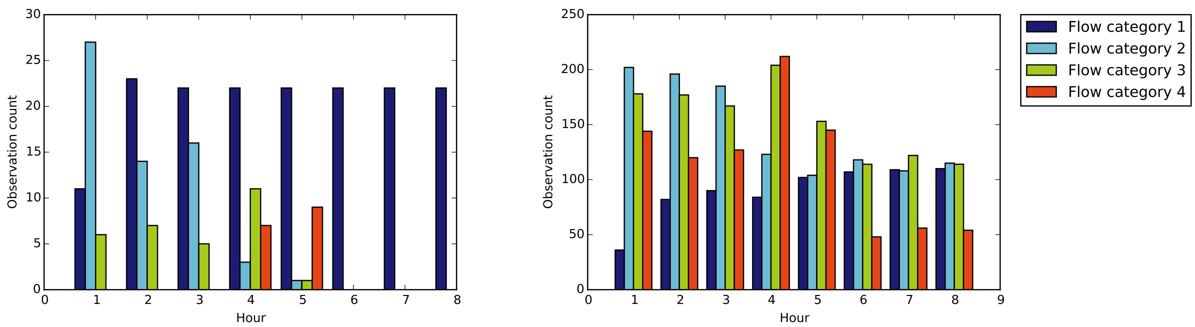


Figure 7.4: Spatial overview of work zone 3 for evaluation of dynamic speed limit

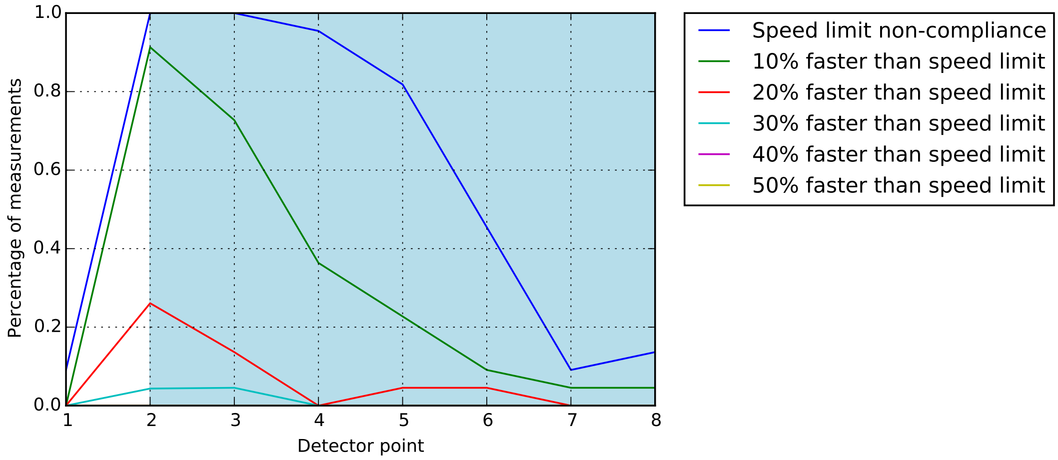


(a) Number of observations in each flow category in phase 2 'No work'

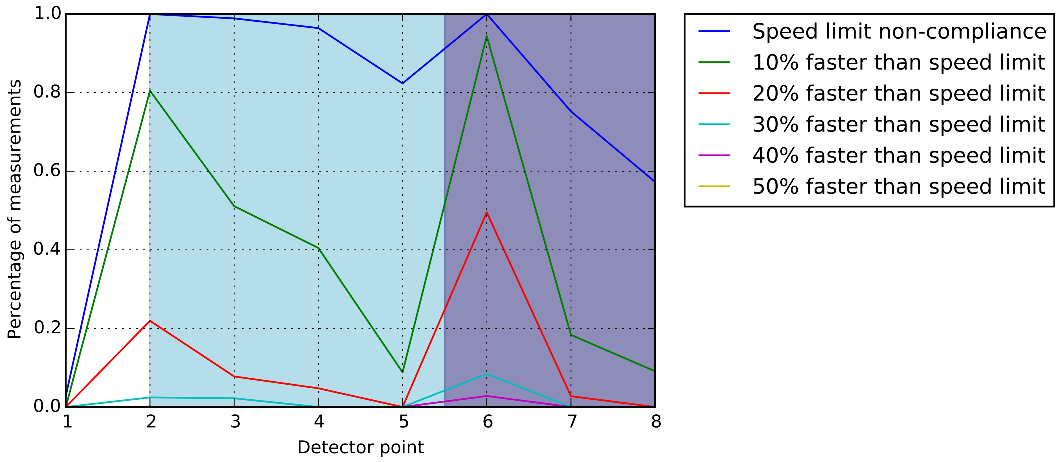
(b) Number of observations in each flow category in phase 3 'Work'

Figure 7.5: Number of observations in each flow category in WZ3 per detector point

Based on Figure 7.5, it is chosen to compare phase 2 with phase 3. In phase 3 the speed limit from point 2 to point 7 is 90 km/h. In phase 3 the speed limit is 90 km/h from point 2 to 4 and from point 5 it is lowered in the activity area to 70 km/h. In Figure 7.6 the 90 km/h area is light blue, and the 70 km/h is light purple. In this figure the speed limit non-compliance is plotted, the percentage of measurements of which the speed is higher than: the speed limit (blue), 10% higher than the speed limit(green), etc. In phase 2 at point 2, none of the measurements of minute aggregated mean speed complied with the speed limit of 90 km/h, as seen in Figure 7.6a. Drivers start to decelerate from this point on, and in the work zone the non-compliance to the speed limit of 90 km/h is decreased to approximately 10% in point 6. In this point, a small percentage of drivers already increases their speed in the work zone.



(a) Speed limit compliance in WZ3 flow category 1 phase 2 'no work'



(b) Speed limit compliance in WZ3 flow category 1 phase 3 'work'

Figure 7.6: Percentage of non compliance in WZ3 of vehicles in flow category 1

In Figure 7.6b, the speed limit non-compliance of work zone 3 phase 3 'work on the crash barrier' is plotted. In this graph, the same pattern can be observed where the non-compliance decreases throughout the work zone. Two speed limits are introduced, and this is shown in the increase of non-compliance in point 2 and 5. At point 2 the first introduction of a new speed limit is from 130 to 90 km/h which is a drop of 40 km/h. The second introduction at point 5 only states a decrease from 90 km/h, to 70 km/h but the non-compliance of 10, 20 and even 30% higher than the speed limit increases dramatically.

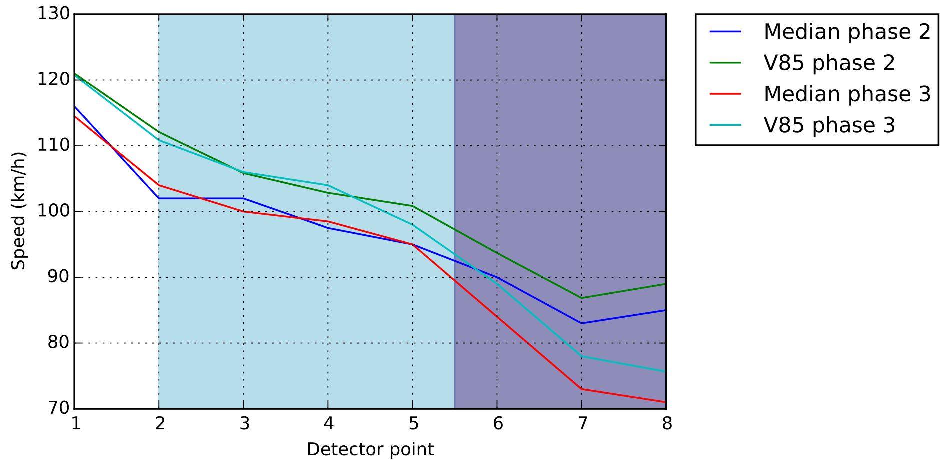


Figure 7.7: Absolute median and V85 speed of WZ3 phase 2 and phase 3 Flow category 1

Figure 7.7 shows the differences regarding absolute speed differences. From point 2 to point 5, there is not much difference. This is also expected since the speed limit in that area is the same in both work zone phases and the same flow category is compared. From point 5 it is clear the speed limit in phase 3 is set to 70 km/h, the speed decreases. What stands out is the speed variation (distance between V50 and V85) which is larger in the 70 km/h zone than the 90 km/h zone. The speed variation has an impact on the traffic safety, if it is larger a road stretch is considered less safe. In this case, the cause of this variation can be two-sided. One possible explanation is that a larger percentage of drivers does not comply with the speed limit or it is due to the more substantial number of measurements in phase 3. Before point 5 the stages act approximately the same, so there is an indication that the speed limit of 70 km/h causes larger speed variation in this area.

8 Verification and validation

In this chapter, the verification and validation of the data analysis and design are explained. First, the model validation is presented in Section 8.1. The verification of the design requirements is presented in Section 8.2. Lastly, the validation of the system design is discussed in Section 8.3.

8.1. Validation of MLRM

To validate the model, the question whether the right model was built needs to be addressed. To answer this question, first the outcomes of the model are validated using literature. The sensitivity of the model is briefly studied and then the assumptions of the modelling method are tested. These analyses result in a conclusion of the validity of the model and possible improvements.

8.1.1. The model outcomes

The spatial profile without temporal or spatial influences (besides the traffic measures and MTM signalling) shows a gradual speed decrease of 5-7 km/h every 400-500 m. Knoop et al. [2009] researched microscopic traffic behaviour near incidents on Dutch motorways. He found a speed decrease on the left lane of 13 km/h and 9 km/h in the right lane in 250m near a non-congested incident. The deceleration is far more than the gradual decrease found in the model. However, in this speed drop neither truck nor flow effects are separated from the speed observation. Knoop et al. [2009] conclude that in the free flow conditions of this incident the drivers may not have realised that their speed had decreased, while this speed drop far more steep than the one found in this research. If all temporal factors are added, the speed drop between point 4 (90 km/h and two lane) and point 5 (70 km/h and one lane) is 17 km/h in 500m. Which is a higher deceleration than that of the incident, but the warning system area can explain that effect.

Traffic flow has a direct relation with traffic speed, the fundamental traffic relation. The outcome of the speed reduction -0.01 km/h per flow (veh/hour) can be compared to the speed/flow relation of Figure 5.3. In the flow/speed relation figure, a parabolic relation can be found with the top located around +- 30 km/h and 2000 veh/hour. After linearising this point, the result is 0.015 km/veh which is in the same order of magnitude as the value found in this research.

The direct speed effect of truck share cannot be found in literature, however assumptions about a truck and cars free flow speed are made in for example the FASTLANE model of Yuan and Hoogendoorn [2012]. The v_{car}^{free} of the FASTLANE model calibrated on the Dutch motorway A15 is modelled as 110 km/h and the v_{truck}^{free} is estimated as 85 km/h, a difference of 25 km/h. This makes the MLRM estimate of 20 km/h/truck-share realistic, as a 100% truck share would mean a reduction of 20 km/h. Since the flow effect is taken out of this variable, the effect can indeed be compared to the free-flow conditions and it is found to be in the same order of magnitude.

PCMS are deployed world wide. Their function can vary from a speed display system to a speed monitoring system equipped with radar. The effect of a PCMS as speed display is previously found to be 6-8 km/h by Goldstein [2012] and 11-13 km/h if equipped with radar by Wang et al. [2003]. These large effects are found on US highways where different speed limits are used and no MTM system is present. The results are found to decrease over time [Brewer et al., 2006]. The findings may be the result of a incidental fright reaction, or PCMS may indeed be far more effective on US highways. The found decrease of 1-2 km/h in this research is better comparable to earlier found speed drop of 5 km/h in the warning area of a simulated work zone using an in-car warning system [Bazuin, 2017]. The DS result is larger, yet only significant in the warning area. The MLRM in this research finds a much smaller speed drop, but found effect is still significant in the work area.

The modelled effect of the on-ramps in Maarsbergen (work zone 1 and 2) and Veenendaal (work zone 3) are very different. They are, as expected, both negative. Yet the on-ramp in Maarsbergen has a far larger effect. This is due to the on-ramps situation in the middle of the work zone. The traffic is already guided in a one lane system, and the on-ramp guides even more traffic in this one lane system. The Veenendaal on-ramp in work zone 3 is a 'normal' on-ramp of which the turbulence is researched by Hovenga [2014]. Hovenga [2014] finds no speed decrease compared to a normal motorway segment on the location of the acceleration lane. The speed drop found 300m upstream of the on-ramp is approximately 5 km/h, which is higher than the MLRM estimate of -2.3km/h. Since Hovenga [2014] finds different patterns but the results are in the same order of magnitude, the results of the MLRM in this research are considered realistic.

Steinbakk et al. [2017] researched the influence of visible roadwork activity on driving behaviour in a video based experiment. The mean speed difference in a comparable work zone was found to be 4 km/h. The instant effect of activity on speed found in the MLRM is -3.5 km/h, this is very close to the difference found by Steinbakk et al. [2017]. The video based experiment is a very different type of research, it researches at which speed participant would drive and prefer to drive under certain conditions. This field trial and the study of Steinbakk et al. [2017] supplement each other.

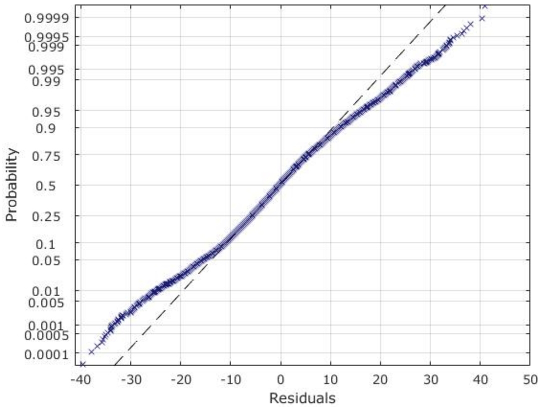
The enforcement estimate of the MLRM is the only estimate which has a different direction than hypothesised. The modelled speed increase is probably due to an influence of one of the other temporal effects. The enforcement was modelled in such a way that it affected the whole work zone, which might not be entirely realistic. The overall MRLM is very spatially orientated using the spatial 'points' profile as a nominal category. The p-value of enforcement is very high compared to all other factors, and the positive effect found is minor. It is probable the spatially oriented model did not optimise the temporal oriented enforcement factor since its effects on individual observations is only small. If enforcement is left out of the MLRM, the model preforms approximately the same. The R-squared is still 0.725, and all estimates are stable. The exact output of this model can be found in Appendix E.1.8.

8.1.2. The model sensitivity

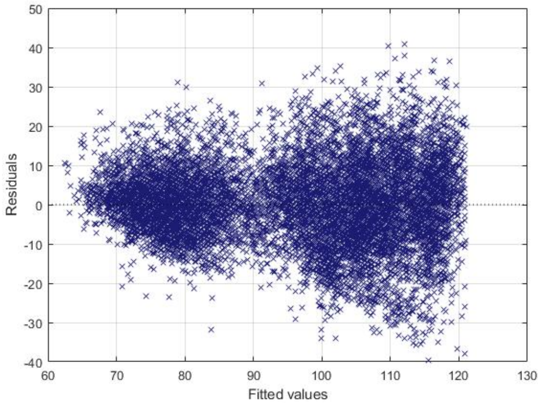
The models sensitivity is tested as well. In this sensitivity test, a part of the data is excluded and it is studied if the models estimates are stable. This could be computed using a random data filter, but in this model one of the work zones is excluded as a whole. This results in a MLRM with 8627 observations and R-squared of 0.717. All estimates stay approximately the same, the total model output can be found in Appendix E.1.9. Only the effect of the PCMS slightly decreases and now is -0.8 km/h ($p=0.03$), the positive influence of enforcement increases to 1.5 km/h ($p=1E-3$). These factors were least significant in the original MLRM so the larger effect on these estimates is expected.

8.1.3. The model assumptions

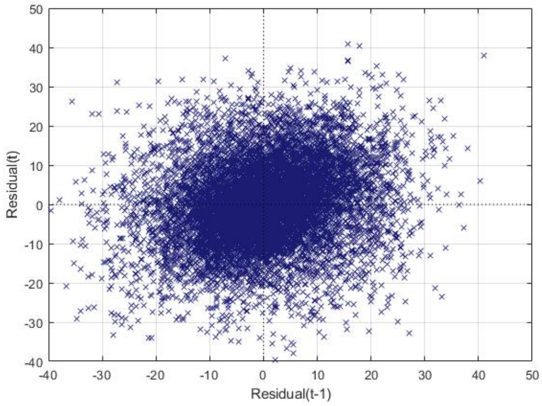
The assumptions of the MLRM are tested in this subsection. Using the normal probability plot of the residuals shown in Figure 8.1a the normal distribution assumption is checked. The errors between observed and predicted values should be normally distributed. It is shown the residuals are somewhat tailed, this implies that there are some extreme positive and negative residuals. Overall the values fit the normal probability properly.



(a) Normal probability of residuals



(b) Plot of residuals vs. fitted values



(c) Plot of residuals vs. lagged residuals

Figure 8.1: Validation of the MLRM

The variance around the regression line should be the same for all values of the explanatory variable. This can be tested using the residuals vs. fits plot. If the variance around the regression line is equally distributed the plot would show an equal band around zero. In Figure 8.1b an increasing trend is shown. If the fitted speed increases the residual variance increases as well. The increase in the variance as the fitted values increase, suggests possible heteroscedasticity. The linearity assumption can be checked using the same figure. The relation between the response and explanatory variables should be linear. In the same plot we can observe the the residuals vs fitted values do not show any distinct patterns like a parabola. This implies the first assumption of a linear model is met, the relation between the response and explanatory variables is linear.

The lagged residual plot in Figure 8.1c shows if there is serial correlation among the residuals. In this figure the plot shows an evenly distributed scatter plot and there is no obvious correlation among residuals. The non existence of multicollinearity is the last assumption of the MLRM which should be tested. If multicollinearity exists, the Belsley collinearity diagnostics would show high condition indices. The result of the test can be found in Appendix E.2, all condition indices are far below values which would indicate multicollinearity.

8.1.4. Conclusion

Although the model outcomes (apart from the enforcement variable) present itself as probable, the model contains heteroscedasticity. The heteroscedasticity influences the precision of the coefficient estimates. The p-values of the coefficients are estimated satisfying the assumption of constant variance. Therefore, the p-values can be incorrect. This can be corrected for using a weighted non-linear regression model.

Another measure which could be taken is a better outlier filter. The outlier filter used computing the model is a standard filter before implementation in the model. The model diagnostics in Appendix E.3 of the Cooks-distance show there are several large outliers which could be deleted from the model.

When searching for a better model to find the effect of the PCMS a model which can include both the spatial and temporal effects may lead to better results. The MLRM used in this study is very spatially oriented and a small temporal factor like enforcement has too little effect on the overall least square optimization method. In spatial temporal models the relation between the points can be modelled more accurately. There is a relation between the observations in work zone 1, 2 and 3, namely the drivers. One could even argue there is a relation between work zone 2 and 3 since they were situated on the same road stretch on the same night. This relation in combination with aggregated (non-subject) data cannot be modelled.

Another possible improvement could be to make the results more applicable for traffic (forecast) models. The aim of this model is to evaluate the results of the field trial. It will be important to create the output of the field trial according to the required input for the traffic models. A Tobit-model proposed by Debnath et al. [2014], which is able to model speed limit compliance using a linear regression model with a boundary level of the speed limit, would result in the effect of the various factors on the speed limit compliance instead of the speed. This may be better applicable in traffic (forecast) models practise.

8.2. Verification of system design

The verification of the design requirements is done according to the research design shown in Figure 3.3. All requirements are verified by observations which are a form of the verification method 'inspection' [Wasson, 2006].

8.2.1. Inform and warn traffic

Two sub-systems informed drivers during the field trial, the MTM system and the PCMS. In work zone 1 and 2 from 75.8 hm, wrong information was issued. In this point X-70-X is shown on the MTM system. However, the work zones' traffic cones stop so it would be logical if this signal showed X-⃠-⃠. Why this was the case has not been investigated, but the main reason is thought to be for flexibility reasons of the work zone. In this case, the exact place of the work was not yet known and a margin was taken. Another option is that the origin of the work zone was at 76.7 and the work zone was merely too short otherwise.

The result of this misinformation is the red cross negation shown in Figure 8.2. Traffic participants get the signal that the lane is closed, yet the traffic measures stopped and the lane looks open. Red cross negation is a serious issue resulting in many accidents so a traffic situation which provokes this behaviour should be prevented in any case.

The information on the PCMS functioned well, so all information regarding the work zone situation was displayed for the traffic participants.

8.2.2. Credibility

The aspect credibility results in three design requirements, again shown in Table 8.1. If we assume that the systems were conspicuous enough for drivers to read, process and understand the PCMS and the dynamic speed limit system, the requirements were met. Whether this is indeed the case is more a question of validation than verification and will be discussed in Section 8.3.3.

Drivers were informed about the work zone condition and even the type of activity in the work zone. This expectation setting should lead to meeting the driver's expectation. If the driver has precisely the same expectation with this text has not been tested. The detailed design of Section 4.6.4 shows that 71% of

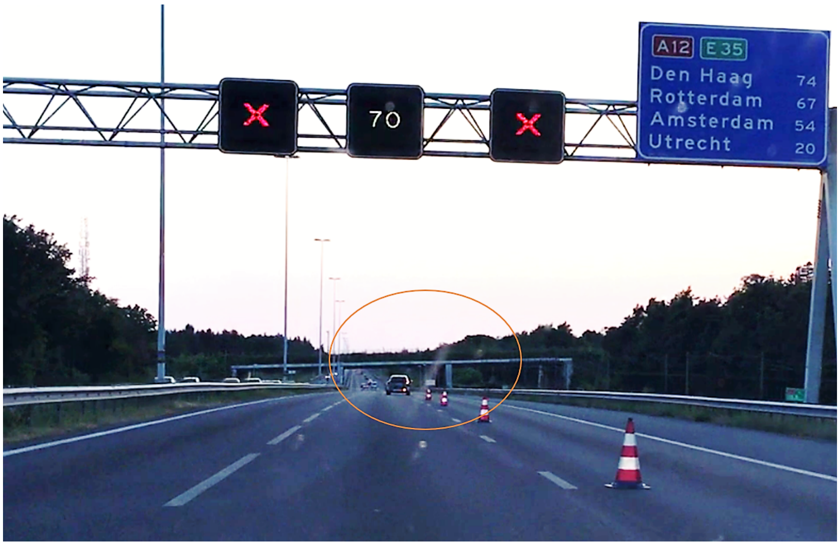


Figure 8.2: Dash-cam image of MTM portal 75.8 and red cross negation of a vehicle

the test population understood the message 'uitvoegend werkverkeer' or merging work traffic. In Dutch this is quite a complicated message since 'uit' or in English 'out' explains the direction of the work traffic.

The information requirement was met via the message on the PCMS. The speed limit was indeed adapted to the work zone condition. The only discussion which could be relevant is: what is the right speed limit? In this case the CROW [2016] guidelines were followed.

Table 8.1: Aspect requirement credibility from Table 4.2

Aspect	Requirement
Credibility	The work zone condition shall meet the drivers expectation
	The traffic shall be informed about the work zone condition
	The speed limit shall be adapted to the work zone condition

8.2.3. Safety

The safety requirements are stated by using examples from Simpkiss [2009]. The first requirement is shown in Table 8.2 and is an all-embracing and maybe ideological requirement. The system is designed with this ideology in mind but health and physical risks cannot be eliminated in traffic. The second requirement states a process to identify and control risks, and this is indeed done in the risk register of Appendix C.2.

The approval of QSHE and the road authority were given. This permission is even substantiated by the approval of the ethics committee of the TU Delft.

Table 8.2: Aspect requirement safety from Table 4.2

Aspect	Requirement
Safety	The system must be designed to eliminate or mitigate safety, health or physical risks.
	Identified safety and health risks will be eliminated, minimized or controlled to acceptable levels(...) within cost, schedule and performance constraints.
	The system design and operational plan shall be approved a QSHE coordinator
	The system design and operational plan shall be approved by the road authority

8.2.4. Operational effectiveness

In the operation swim lane diagram of Figure 4.6 three operators stand out. The operator in the traffic management centre, the foreman traffic measures and the researcher. Two operators are mentioned in the operational effectiveness requirements in Table 8.3. The operational effectiveness requirements were met in this field trial. It proved feasible to explain the necessary steps to the foreman via telephone. The traffic operator was not overloaded.

This was influenced by the help of the researcher. The researcher was called by the foreman and changed the PCMS. The changing of the PCMS is done via an online website which could be reached by mobile phone. For the foreman, this platform made calling the researcher just as time-consuming as changing the PCMS himself. The solution could be implemented just as easy without the researcher. A possible hindrance factor would be that of computer ignorance among foremen.

Table 8.3: Aspect requirement operational effectiveness from Table 4.2

Aspect	Requirement
Operational effectiveness	The workload for the traffic operator shall be within a operation time of 10 minutes
	The workload for the foreman traffic measures shall be within a operation time of 10 minutes
	The system shall be explainable within 15 minutes of training for the traffic measures foreman

8.3. Validation of system design

Field trials and acceptance tests are well-known validation methods [Wasson, 2006]. In this section, the validation of the designed system is discussed. The user acceptance would follow from a valid acceptance test. The system integration and performance follow from the field trial.

8.3.1. User acceptance

The originally proposed user acceptance test was not possible due to the maintenance of the gas station. A questionnaire was created to ask if and how drivers experienced the system. This would be placed at the gas station located right after the work zone.

Because this wasn't possible, a new method was found. Using the available dash-cam images a questionnaire could be created. The 'experience' of users would be downgraded to video image. Since this research aims at behavioural validity, a questionnaire like that would not fit into this research framework, even with a 'before' and 'after' test according to the framework of Van der laan et al. [1997]. It would be more useful to find and test what 'credibility' of work zones is and then test if this system meets the requirements. However this would be a new research itself.

Other system users than the drivers, the traffic operation centre and contractor, were positive about the proposed system.

8.3.2. System integration

The process of system integration is making sure all the individual sub-systems work together for the same cause. The integration of the designed system is not very complex as there are little interfaces between the system components. Most of the software and hardware components work individually from each other. One could say that the PCMS part of the system was simply added and not integrated.

Since all the system components are included in the operation process, this is not completely true. The PCMS was integrated in the operation system. The traffic management centre also has the ability and software to login to the online PCMS system. The systems are not fully integrated, but steps are taken to stimulate this integration. It was however chosen, personnel resource reasons, not to integrate the systems in this trial.

Looking at the system as a whole, the sub-systems of MTM and traffic measures are well integrated into the designed work zone number 3. In the comparison work zone of 1 and 2 this is much harder to say since the red cross issue is proof of bad integration. Whatever the reason for this layout, the MTM system and traffic measures do not work together as they should. For this reason, it is fair to say that steps can be taken to improve this integration, and again recommendations from this research may contribute to that cause.

8.3.3. System performance

The objective of the system was to increase speed limit compliance in the work zone by increasing the credibility of the work zone. The speed limit compliance and speeds in the work zone during the field trial were measured and compared to another work zone without the designed system. In Chapter 7 this comparison is described and in Section 8.1 the validity of these results are discussed.

Although the model contains heteroscedasticity, the model estimates are probable. The PCMS has a small and over the length of the work zone decreasing effect on the speed of drivers of -1 km/h. Other factors like on-ramps and visible work activity are more influential in decreasing drivers speed. The system slightly improved speed limit compliance, but it is not proven this was because of higher credibility. Other explanations of this speed decrease caused by the PCMS could be that drivers wanted to read what was on the sign, but the text did not influence their speed choice. Or drivers were influenced by the lights of the PCMS and this effect caused the small speed decrease. Using the last explanation one would however not expect to find such a significant result. So, the PCMS increases speed limit compliance, but it is not proven this is due to increased credibility.

The dynamic speed limit system also improved speed limit compliance in case of a speed limit of 90 km/h. There is also an indication that the variation of the speeds decreased in the 90km/h phase, but this could also be due to the lower number of measurements. It is unclear if the dynamic speed limit influenced the credibility of the empty work zone.

9

Conclusions and recommendations

In this chapter, the most important conclusions and recommendations following from this research will be discussed. The answers to the research questions of Section 3.1 are presented in Section 9.1. The scientific contributions of this thesis are discussed in Section 9.2. The practical implications are presented in Section 9.3. Section 9.4 presents the recommendations for future work.

9.1. Findings and Conclusion

Speeding in motorway work zones is a safety issue for both drivers and road workers. That is why the objective of this research was stated as:

To design and test a new speed management measure for Dutch motorway work zones which improves speed limit compliance by integrating HF requirements into the system design.

To reach this objective several research questions were stated. These questions are answered in this section. Starting with the first research question:

How can the current Dutch motorway work zone system be described?

Using a system engineering approach, the current concept of operations and its stakeholders were found. The objective of a work zone is to facilitate traffic, while also facilitating a safe working environment. The last part of the objective is stimulated from the Dutch labour law. Work zones in the Netherlands are designed according to the CROW design guidelines. These design guidelines are created by a collaboration of employers, road authorities, training institutes and law enforcement. Another essential process involved is that of the 'minder hinder' (less nuisance) method of the road authority. In this program, it is studied why and how drivers experience nuisance from road works and what can be done to prevent this nuisance. In all layers of the work process, from awarding a contract to the approval of a work zone, the less nuisance process is incorporated in the decision making.

In the process of 'creating' a work zone, two major parties are involved: the road authority and the contractor. The road authority often awards a project to a contractor who, with or without an SPV, designs the work zone. The work zone is then approved in the system SPIN by the traffic counter which acts within one of the six districts of the road authority. In case the MTM signalling system is available, the right MTM layout will be put in the software and processed. The traffic operator can put it on the lane signalling system on the day of the work zone.

On the night of the work zone, the foreman responsible for traffic measures contacts the traffic operator who approves the request based on the current traffic situation. In that case, the layout is put on the MTM system and the foreman can start placing the work zone. This is a hazardous job since a safe working environment is in the process of being created. A truck with an action car and crash-attenuator is used to protect the vehicle from which the workmen place the traffic cones. The work zone is created and the actual work crew merges into the work zone. The merging of work traffic can be described as hazardous as well, but this depends on factors such as the work zone layout and type of equipment. The planned work is executed and afterwards the work zone is removed by the traffic measures crew. After the removal, the foreman contacts the TMC to remove the MTM measures.

The speed limit is defined on the basis of the type of work. Speed management from a HF perspective or the speed management framework of SWOV is not included in this practice.

What design method can be used to incorporate HF requirements in the system design?

As stated in the research objective and problem description early in the research stages, it is chosen to incorporate human factors into the system engineering design method. Due to the novelty of this approach, it had to be studied carefully. The Human System Integration framework provides a solution for this question. HSI is a method used by the NASA and USAF to incorporate human factors into system design [Simpkiss, 2009].

The incorporation of the five key principles was straightforward and the V-model proved to be usable for the HSI method, although some literature suggest alternative models [National Academy of Sciences Committee on Human-System Design support for changing Technology, 2007]. The most challenging task was stating the design requirements. This is elaborated on in the following research question.

What are the HSI requirements for an improved system design?

Several HSI aspects are found of which requirements are stated. Operational effectiveness was an important aspect for the feasibility of the field trial. Safety is a common non-functional system engineering aspect and has a lot of connections with HSI. The most important design requirement was the aspect credibility. In literature, the credibility of speed limits was found as a cause of speeding. Thus this is also a relevant aspect of speeding in work zones, although it is difficult to implement [SWOV, 2012a]. Due to the HSI framework, it could be incorporated in the design process.

From the aspect of credibility, precise requirements had to be created and for this literature is used as well. The final report of the european road work safety research initiative (ASAP) stated credibility as: "A credible speed limit is in line with the driver's expectations [Sorensen et al., 2015]". This is a very practical explanation, so this explanation is used as a design requirement. The explanation of credibility can also be: "Credibility means that drivers consider a speed limit as logical or appropriate in the light of the characteristics of the road and its immediate surroundings [Goldenbeld and van Schagen, 2007]." Or it can be defined as: "If speed limits are regularly not in line with the characteristic of the road and the road environment, the speed limit system in general may be questioned by drivers [Goldenbeld and van Schagen, 2007]." Finally the SWOV [2016] gives: "Explanation of why a limit does not suit the road image can also be helpful in increasing the credibility." In work zones, the credibility is often linked to inactive work zones.

The most practical and technical explanation of credibility is used as the overall credibility requirement: the work zone condition shall meet the driver's expectations. To incorporate the workers' perspective, the work zone phases are introduced. Four stages are identified in the work process which have specific hazard characteristics: the placement of traffic measures, a time of no active work, the work itself and the removal of the traffic measures. The requirements state that the road user shall be informed about the phase and the speed limit shall be adapted to the work zone condition.

How can a new speed management system be designed which integrates these HSI requirements?

Incorporating the credibility requirements, the information and speed limit of the work zone had to be adapted. This is done using a (more) dynamic speed limit on the MTM portals and a PCMS is added for the information component. The PCMS showed four messages: 'Placing traffic measures', 'No active work', 'Work on the crash barrier' and 'Removal of traffic measures' all accompanied by the road work warning sign.

The speed limit is made 'more credible' by changing it according to the work zone condition. In the time no activity was conducted in the work zone, the speed limit was increased from 70 km/h to 90 km/h. Using the speed limit of 90 km/h was not a design choice but was restricted by the MTM system. Because of ethical and time limitations, the PCMS was chosen over in-car technology because it was 'proven technology'.

The design was validated using a field trial in which the effect of the system on the traffic could be measured. This also allowed the integration of the system and operational effectiveness to be verified.

What are the effects of the designed solution on the traffic system?

To search for effects of the designed solution, a field trial was conducted on a Dutch motorway. A field trial ensured the behavioural validity of the results. The desirable effect is a significant speed decrease in the experimental work zone system, which was found using an MLRM. The PCMS was modelled as a dummy-variable with an effect of 1 on the location of the PCMS and the value decreases over the length of the experimental work zone. The resulting effect was -1.25 km/h with CI of [-0.6,-1.9] and a p-value of 1.78E-4. The spatial impact of the PCMS is significant up to 2.7 km downstream. However, uncontrolled factors from the operating environment like truck shares (-20 km/h), flow (-0.01 km/h) on-ramps (-12 and -2 km/h) and the work zone visible activity (-3 km/h) are far more influential than the designed system. The MLRM is contaminated with heteroscedasticity which influences not the estimates, but the p-values and confidence intervals of the model.

The dynamic speed limit influenced the speeds and increased the speed limit compliance. There is also an indication the (higher) dynamic speed limit decreased the speed variation, this cannot be tested due to lack of comparable work zones and the low number of measurements during this phase.

9.2. Research Contribution

The first research contribution is the integration of system engineering and human factor research. In traffic (safety) research the human system integration (HSI) approach has never been used before. The design guidelines of intelligent traffic systems (ITS) in the U.S. state that an system engineering approach should be taken. The design guidelines of all Dutch roads and temporary traffic situations are based on the HF principles of sustainable safety. The HSI approach is used in practice, but in other industries such as the army [Simpkiss, 2009] and space system design [Tadros, 2013].

The implementation of HSI led to several insights, especially in stating HSI requirements. The HSI principals of (1) stakeholder satisfaction and (5) risk management proved to be essential. The HSI V-model of Figure 3.3 can be implemented in many other design orientated research. For example, it could provide integrated solutions for the design of in-car ITS systems or drone systems on building sites.

The research also gave insight into how a field trial can be evaluated using loop detector data. The project proved minute-aggregated loop detector data is complicated to provide insight into microscopic field trials. Although there was enough data, no vehicle paths could be identified which would have led to individual 'participants' in the trial. Lacking research participants, many statistical methods for repeated measurements tests could not provide answers towards the effects of the measure. The multiple linear regression model is proven to be a feasible method, but it has its own disadvantages. The detector points and corresponding motorway traffic management portal are incorporated as a categorical factor in the model. This is done to create a spatial profile, but using the spatial/temporal data resulted in a model which contains heteroscedasticity.

For future work, it is advised to use other measurement techniques like the not aggregated loop detector data or video imaging techniques. In this manner, individual vehicle paths can be determined and speed profiles can be created. The same statistical techniques as for driving simulator studies are then available to the researcher. Since truck shares have a significant impact on the speed in work zones, it is also recommended to incorporate those in any future field trial evaluation. Also, it is advised to use the same road stretch for the experimental and non-experimental zone. This decreases the complexity of the evaluation, since other spatial influences like on-ramps proved to have a significant influence in this trial. In this kind of experimental research it is unknown whether the data will provide significant results, but conducting conducting a trial multiple times will decrease this risk. And lastly, it proved useful to observe the trial with cameras and create dash-cam images of the work zones while the measurements were taken. These videos gave insights in the measured speed data. This is recommended to do in future field trials as well since it is almost impossible to oversee and control all factors which prove to be relevant beforehand.

The research also contributed to the field of speed management in work zones. The research is an addition to Table 2.1 which summarizes previously tested solutions world wide. To the researchers knowledge, it is the first project to explicitly attempt to optimise the credibility of a work zone. However, projects with variable speed limits or providing extra information are attempting approximately the same. Small yet significant results were found in this research and the design looks promising.

9.3. Practical Implications

The practical implications of this research are two-sided. The commissioner of this research, BAM Infra, would like to use the findings from the research in practice. Also, the entire work sector was involved in this study (from QSHE to the road authority) and they can also use the outcomes of this research.

9.3.1. Implications for BAM Infra

The HSI design model used in this research can be used in the design of new infrastructure projects. Not only traffic management, but environment management and QSHE can profit from this integration of all human factors. These departments have a 'reporting function' [Muralidhar, 2008] and are called 'rest processes' in the Koninklijke BAM Groep nv [2008] system engineering guidelines. Since many construction companies today strive for digital construction, the HSI framework also has the potential to improve these systems. The HSI framework has already proven its added value in projects for 'unmanned' weapon system design of the USAF, so it could also be relevant for innovations such as drones on building sites.

BAM has the ambition to innovate and work on futuristic projects like 'smart motorways' and 'smart mobility'. A large contractor like BAM Infra has the knowledge and resources to arrange for field trials and tests. It is recommended to use the insights of the evaluations of this trial. It is essential to search for appropriate statistical evaluation methods to evaluate experimental designs.

In some kinds of work, empty work zones are unavoidable. For this field trial the situation was simulated, but in practice empty work zones exist on motorways as well. Changing the MTM system to a higher speed limit (90 km/h) instantly is currently impossible. If this situation is foreseen and incorporated in the planning, the more credible speed limit system is feasible. It is possible within the current system by requesting two extra SPIN measures. Calling the traffic management centre to change the speed limit is not a very time-consuming task. So if necessary and reasonable, this system should be implemented in empty work zones regardless of whether the PCMS is implemented. It improves the credibility of work zones and thus the safety of employees in work zones. A non-work zone associated speed limit like 100 km/h may have more substantial effects.

The effect of the PCMS is minor, so it is exaggerated to recommend the deployment of the system in each work zone. However, the essential goal of the system, the information combined with the designed speed limit, can be optimised and even used for future in-car technology or other 'smart mobility' applications.

9.3.2. Implications for the sector

BAM Infra is unlikely to resolve the problem of speeding in motorway work zones by itself. The sector as a whole has to work together and through this research it has become clear that a large awareness of the problem is already present within the sector. Following from this awareness, a willingness to cooperate in the solutions is found by the researcher.

Regarding the CROW guidelines, several implications of this research are found. The first suggestion is that stating a 'safe' speed limit, although legally binding, does not create a safe working environment. Speed limit compliance in work zones is low. Credibility and work zone nuisance targets contain overlap, but the credibility of work zones could be a new aspect of work zone safety in the guidelines.

PCMS's are deployed for several reasons. Their effect on traffic was unknown and now it is proven they have a slight speed decreasing effect. However, it has not been proven whether this is due to the message and how important the message is. This could be an addition to the CROW [2017] guidelines on information on dynamic message signs since in these guidelines no information on the effect of PCMS's is mentioned.

Improving the credibility of work zones is a goal for every party involved in the work zone sector. If one contractor or authority does not cooperate, the credibility of speed limits in work zones will fail. The responsibility of credible speed limits is one for the entire sector, but drivers have a responsibility as well. Drivers are often unaware that decreased speed limits are related to the proximity of workers to the traffic. Drivers have a lot to complain about work zones and clearly experience nuisance, but programs like 'less nuisance' incorporate these wishes already. 'We', not as a sector but as a society, have to realise that road work is unavoidable. Investments in the last step of the SWOV speed management framework 'information and education' are recommended by the researcher.

9.4. Further Research

The proposed HSI design method could be further researched. In this research, it is implemented in a specific design assignment. Stating the HSI requirement proved to be difficult, but verifying these requirements proved even more difficult. Did this design indeed achieve 'the work zone condition meets drivers expectations'? Wasson [2006] proposes verification methods which are sometimes unsuitable for HF requirements. The effect of a design on human behaviour is difficult to prove since ideally both the stated information (what a person thought) and the observed/measured behaviour is available. HF research has many methods which are suitable for the system design methods according to Tadros [2013]. It should be researched how this can be incorporated, since the verification of the HSI requirements is a missing link in this research.

In this design, the V-model is used since it is common practice in the construction industry. National Academy of Sciences Committee on Human-System Design support for changing Technology [2007] propose a different design model, The incremental commitment model, which may be a more appropriate method. The model differs from the V-model in this research, in that stakeholders are involved and committed in every design phase. At the end of each phase the design risks are assessed by the stakeholders and the transition to the next phase is discussed. The phases are: Exploration, Valuation, Architecting, Development & Architecting and Operation, Development and Architecting. In comparison to the V-model, the incremental commitment model focusses on risk driven development and establishes explicit feasibility factors as pass/fail milestones. The model could be further researched by first comparing the methods and then implement the incremental commitment model in a project. The outcomes may lead to a combination of both methods which is suitable for the design of speed management measures.

Many mention that the credibility of work zones and its speed limits can improve speed limit compliance. Research has been done into speed limit credibility and nuisance perception of drivers. No research is found which defines the credibility of work zones. It is recommended to study this further because finding the definition and factors which influence credibility, may lead to better speed management measures. Methods which include possibilities for stated preference research, such as driving simulators or (video) questionnaires, may be better suited for the purpose of defining credibility in work zones.

The evaluation of the field trial proved to be difficult. The used MLRM contains heteroscedasticity which can be corrected for using non-linear regression models with weighed least squares methods. In the evaluation of network performance, spatial-temporal statistical models are used. This method may provide an even better solution to evaluate microscopic field trials using aggregated loop detector data. These more realistic models may lead to realistic traffic models of work zones which currently do not incorporate speeding. The creation of a Tobit model as proposed by Debnath et al. [2014], which models speed limit compliance instead of speed, may also be a beneficial next step for both research and practice. Whether to model speed or speed limit compliance depends on the modelling method of the microscopic traffic model in which it can be incorporated in.

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A

Interiews and meetings and expert opinion

A.1. Interview Berend Brinkhuis 14-02-2017 [Dutch]

Achtergrond onderzoek Story builder is een manier om een 50-tal story's , scenario's met de factoren die daar aan bij dragen in kaart te brengen. Een van die story's is struck by a moving vehicle. Door de arbeids-inspectie zijn allerlei arbeidsongevallen op die manier structureel in kaart gebracht. Het scenario 'struck by a moving vehicle' was interessant maar het gaat over alle aanrijdingen. Ook treinen die spoorwerkers aanrijden en ook heftrucks die personeel in magazijn aanrijden. Dus het doel van het onderzoek was om te kijken of dat model wel klopte, en om het specifieker te maken voor wegwerkers.

Een andere aanpak was om te kijken hoe die scenario's nou in elkaar zitten ze te vergelijken met 18 ernstige ongevallen die geregistreerd waren door de arbeidsinspectie. Wij hebben niet zoveel invloed op snelle voorbij-rijders. Wel op onze eigen mensen. Daarnaast hebben we gekozen voor een enquête (een aardig grote), die is afgestemd met het SWOV in die tijd.

De resultaten en aanbevelingen van het onderzoek zijn maar weinig overgenomen. Er wordt nog steeds weinig en slecht gedocumenteerd. Rijkswaterstaat vind het wel een belangrijk thema, echter de meeste ongevallen gebeuren bij lokale overheden. Deze doen daar nauwelijks wat aan en zijn vooral bezorgd over de doorstroming. En dat is dus eigenlijk mislukt. Deze waren ook ondervertegenwoordigd op de expert-meetings. Terwijil daar vanuit veiligheidsoptiek heel veel te doen valt omdat je om iedere vierkante meter moet strijden met het verkeer.

Wij zijn momenteel bezig met twee ongevallen die vielen vorig jaar onder verkeersregelaars. Dat is een werkgelegenheidsproject met een opleiding van 1 dag. En ik denk dat dat een heel kwetsbare groep is en wij als BAM moeten daar meer van weten. Hoe regelen we dat, wat krijgen zij in hun opleiding te horen. In veel contracten staat dat wij geen VRI's mogen plaatsten maar het moeten oplossen met verkeersregelaars. Onze insteek is dat ze kwetsbaar zijn dus ik heb 2 collega's gevraagd een onderzoek op te zetten. Eén aspect is hoe het zit met hun opleiding, het tweede aspect is hoe gaan wij daar mee om. Hoe zetten wij ze in. Daar komen vast interessante leerpunten uit, want ik denk dat de opleidingen tekort schieten. Het onderzoeksplan verwacht ik volgende week en dan gaat dit project draaien.

Een ander actueel onderwerp is dat van een ongeval 2 jaar geleden in Veldhoven. Daar gebruikte fietsers en voetgangers ons werk ondanks de afzetting wel als doorgang. De zijweg was eigenlijk afgesloten voor het verkeer maar fietsers negeerde die afzetting. Een oude vrouw deed datzelfde en wilde oversteken toen ze weer op de openbare weg was. Ze was gewend dat de auto's van rechts kwamen maar door de omleiding kwamen ze van links. Deze vrouw is helaas aan haar verwondingen overleden. Toen was onze conclusie dat wij ook een maatschappelijke verantwoordelijkheid hebben. In dit geval hielden wij ons aan de regels en was alles afgestemd met de Gemeente, maar het was bekend dat fietsers daar gewoon overstaken. Moeten wij daar dan niet iets mee, dat we het desnoods met kippengaas afzetten zodat die mensen gewoon omrijden. We hebben daar toen uitgebreid onderzocht ook als leertraject en moeten we niet kritischer kijken naar die CROW richtlijnen. Dit soort incidenten zeker met fietsers hebben we helaas veel vaker. Want het gedrag wat die fietsers vertonen is natuurlijk dom, dat moet je niet doen. Maar moet je als je weet dat mensen dit gedrag vertonen daar dan geen rekening mee houden?

Uit de bron database vallen wel veel ongelukken plaats waar 'werk in uitvoering' in betrokken is. Of daar echter ook wegwerkers als slachtoffer vallen is vrij onduidelijk. Die dodelijke (verkeers)ongevallen worden inderdaad vaak onderzocht door de politie, niet door de arbeidsinspectie. Tenzij er een werker als slachtoffer valt. Ook onze meldingsdatabase is nog niet volledig aangezien wij van verschillende werkmaatschappijen naar één BAM Infra zijn gegaan een aantal jaar geleden. Ook gebruiken wij nog geen landelijke melding app, daar zijn we wel volop mee bezig.

Wat is er verder gebeurd met de modellen die jullie opgesteld hebben? Daar gebeurd nauwelijks iets mee, story builder was een gebruikersonvriendelijk programma. Daarna is een programma gebouwd met een andere interface maar daar hoor ik op het moment erg weinig van. Het is wel een heel interessant concept omdat je daar ook de blootstelling in kwijt kon. Wij als BAM hebben dagelijks ongeveer 2500 mensen op de openbare weg werken, en zijn zeg 6 uur bezig. Dan kun je dat uitwerken tegenover andere risico's. Daar zijn we momenteel wel volop mee bezig. Aanrijdgevaar is binnen de BAM infra het meest gemelde incident. We zijn bezig met een overzicht van alle meldingen binnen BAM infra genaamd Safety Case. Zodat we beter en gestructureerde risico's kunnen aanpakken. Dit doen we volgens het engelse 'Safety Case' model die gebaseerd is op dezelfde (europese) normen echter heel anders ingevuld dan de nederlandse (ENE). Het safety case model begint met het waarom en dan hoe je aan het werken bent etc.

Het aanrijdgevaar leeft dus zeker onder de mensen aangezien het vaak gemeld wordt. Het gaat echter niet zo vaak echt mis. Komt dat dan door de kwaliteit van de richtlijnen? Werken die blijkbaar goed genoeg? Godzijdank zijn ongevallen een zeldzaam verschijnsel. Als je op een gemiddeld kruispunt gaat staan gaat het erg vaak bijna mis in een uur maar mensen trappen gelukkig net op tijd aan de rem.

Berends focus zou liggen in de dialoog met de opdrachtgever, die hebben hier geen oog voor. Dat de schaarse ruimte zeker in de stad delen met de weggebruiker. Er zijn ook veel kleine aannemers die geen afzetting gebruiken, gewoon met hun vraagmachine beginnen. Die fouten hebben veel te maken met economische overwegingen. Veiligheid is in een diep economisch dal nou eenmaal niet de prioriteit, ook al zeggen we dat wel.

Bij ongevallen hebben we het vaak over de veiligheidscultuur, maar cultuur is traag. Er is echter in de veiligheidskunde ook zoiets als het veiligheidsklimaat, dat kan veel sneller omslaan. Daar hebben wij invloed op, iemand met alcohol achter het stuur bijvoorbeeld niet. Dan kun je nog zoveel borden neerzetten, maar zeker die ongevallen krijg je ook bijna niet onderzocht als KAM afdeling zijnde.

Cijfers en het gevoel zijn ook erg betrekkelijk. Bellen achter het stuur bijvoorbeeld is helemaal niet zo'n grote ongeval oorzaak. Plaats 6 (7%), en politici willen dat per se verbieden. Handsfree bellen? Nee niet per sé. Je zou in de EU auto's moeten maken waar maar 1 stuur in zit. De passagier is namelijk de grootste afleiding in de auto. Maargoed die problemen gaan toch verdwijnen met Uber en zelfrijdende auto's etc.

Het aanpassen van veiligheid(bijvoorbeeld het plaatsen van meer bakens) moet wel in de richtlijnen gebeuren. Dan gebeurd het in de hele branch en hebben we een level playing field. Opzich is daar namelijk niks op tegen. Ik heb het persoonlijk wel eens gedaan dan zie je dat veel minder fietsers en voetgangers deze negeren.

Zo hebben we bijvoorbeeld een onnodig ongeluk gehad in Heemstede. Een oude dame was haar boodschappen aan het doen en wij moesten werkzaamheden verrichten en die pasten net in de grootste bestelbus die je zonder vrachtwagen rijbewijs mag rijden, er hing ook een grote aanhanger achter. Die werkman wil aan het werk en zet zijn auto even op de stoep, hij overlegt even en wil zijn auto wegzetten want die stond in de weg. Hij moest achteruit, zag helemaal niets en is over die mevrouw heen gereden. Dan krijg je de discussie, moeten we niet van te voren dat soort plekken gaan bekijken. Maar dat kan niet voor alle werkzaamheden overal. Slimme ideeën waar Berend wel eens aan heeft gedacht zijn auditieve en visuele signalen voor wegwerkers. Zoals vachtwagens met sensoren. Maar ook bakens die licht geven als er iemand langs rijdt. Etc.

A.2. Site visits

Site visits did not directly contribute to the project, they however helped for the professional opinion of the researcher. The lessons learned are summarized in this section.

A.2.1. Uithoflijn 07-02-2017 & 29-02-2017

The Uithoflijn is a project which constructs a tram in the centre of Utrecht. The work zones are urban work zones but suffer from speeding drivers as well. On some sites the project decided to use more static barriers and screens, not to prevent speeding but to prevent the impact of speeding. The project implemented a speed monitoring display for the bus drivers on the bus line who speed passed work zones. Johan Bekendam and Frank Baelde contributed to a site visit with traffic measures inspection. During the inspection several stories about speeding in work zones were told, such as the trash can example mentioned in the main report.

A.2.2. Ruiterkade 14-03-2017

The Ruiterkade is an urban project in the city centre of Amsterdam. The project uses, next to static signs, a PCMS to warn drivers about the work zone and the decreased speed limit. The project does not have the idea this helps.

A.2.3. Audit roadworks 02-04-2017

During a road works audit of a confidential organisation, secret visits were made to work zones named in the vanAnaarBeter.nl public road work database. It were weekend road work zones. Most work zones named in the nuisance database were not present, two were present but did not have visible activity, and 1 active work zone was visited. No conclusions can be drawn about the activity of work zones.

A.3. Meetings for design and deployment of field trial

The design and deployment of the field trial was created in an iterative process in which the opportunities and risks of each design were a central

A.3.1. Rijkswaterstaat GP, Rijswijk 03-04-2017

The goal and ambition of the project are discussed with Rijkswaterstaat, national projects. The ambition is to perform a field trial, which is indeed ambitious in the given time. It is discussed the design will be created functionally(SE). As to what the design should contain the researcher thinks especially dynamic speed limits are promising. Rijkswaterstaat is supportive of this trial since they also recognize the problem. RWS chose not the contribute to the European BROWSER research project because their traffic measures were not realistic enough. They however like to contribute to a project which is realistic in the Dutch context. The possibilities towards the MTM system speed limits are limited. The problem of empty work zones is not officially recognised as they are, on paper, non existent on motorways.

100 km/h is a impossible speed for the MTM system to show.

risks for deployment of field trial:

- The location of the field trial should not create traffic jams so maybe not the west of the Netherlands (Researcher)
- A longer test period is favoured because of the better measurable impact on traffic (Researcher)
- A initial situation measurement should not deviate too much or have the same location (Researcher)
- no narrowed lanes (Researcher)
- Informing traffic may create safety risks (RWS)

risks for project:

- Time risks (RWS)
- District have to be involved (RWS)

A.3.2. BAM Infra Verkeerstechniek, Den Haag 13-04-2017

BAM Verkeerstechniek Den Haag recognizes the problem as well. They think possibilities are hard traffic measures like chicanes. An other possibility would be emotional messages like 'my father works here'.

Accidents with action cars and the shock absorber truck are also discussed. These crashes are not part of the research scope yet they are frequent and of major concern in the sector. The exact work plan of a traffic measures crew is discussed including the actions of the shock absorber trucks driver. The shock absorber truck driver is the foreman of the crew and is responsible for the safety of the team.

A.3.3. BAM Infra Verkeerstechniek, Culemborg 04-05-2017

Again the problem is recognized by BAM Infra Verkeerstechniek. The possibilities for dynamic speed limits in the lenght of the work zone are limited in the opinion of the representative of BAM Infra Verkeerstechniek. In most work zones the total length of the work zone is used for machinery etc. Also, for the work crew, it becomes unclear in which part of the work zone which distance of clearance zone exists.

Possibilities for dynamic speed limits in time are there since indeed, short term, empty work zones exist. The most dangerous work zone phases are that of the placement and removal of traffic measures and merging work traffic. Although, sometimes, merging in front or behind the work zone is possible and that is not as dangerous as merging between traffic cones in the middle. The last exercise is a difficult, and dangerous task.

BAM Infra Verkeerstechniek has a speedometer which can be used for the test.

A.3.4. Poort van Bunnik, 16-05-2017

The design as is is discussed, a work zone with a heightened speed limit (90 km/h) in inactive work zone situation, 50 km/h in dangerous situations(merging and building/removal of work zone) and 70 in case of 'normal' work zone conditions.

Poort van Bunnik as well recognises the problem and is open to a collaboration for a field trial. This project arranges work zones for RWS Midden Nederland (MNL) and the road authority has to be involved in the project. Therefore together with the road works planner of Poort van Bunnik a project is searched and RWS MNL is involved as soon as possible. A night work zone is chosen for the field trial which is repeated in the same week so initial measurements are possible.

risks for deployment of field trial:

- Informing traffic may create safety risks(RWS)
- The road operator has to help and change the standard road operation (PvB)

risks for project:

- Time risks (RWS & PvB)
- District have to be involved (RWS & PvB)

A.3.5. Rijkswaterstaat GP, Rijswijk 30-05-2017

The design as is is discussed, a work zone with a heightened speed limit (90 km/h) in inactive work zone situation, 50 km/h in dangerous situations(merging and building/removal of work zone) and 70 in case of 'normal' work zone conditions.

Rijkswaterstaat GP still is behind the plan, yet 50 km/h is unlikely to be approved by the traffic centre.

risks for deployment of field trial:

- Informing traffic may create safety risks (RWS)
- The road operator has to help and change the standard road operation (PvB)
- 50 km/h is unlikely to be approved, and maybe even impossible in the MTM system. (RWS)

risks for project:

- Time risks (RWS & PvB)

A.3.6. Poort van Bunnik & Rijkswaterstaat MNL, Bunnik 31-05-2017

The design is discussed again. RWS does not recognise the problem of empty work zones since normally, directly after the placement of the traffic measures, work starts. If you want to differentiate the speed limits, for every phase a SPIN request has to be created. One of the problems is, that if you place 70 km/h people probably drive 90 km/h, etc. If you want to do your work really safe, the speed limit in work zones should be 50 km/h, which is politically infeasible.

The speed decrease of 50 km/h which is suggested in the design is probably infeasible in the RWS organisation. PCMS are used often to explain empty work zones for example, however nobody knows the effect of those PCMS's. It is not known if and how many people read them, and what is the effect. 50 km/h is only applied in a traffic jam context.

risks for deployment of field trial:

- Informing traffic may create safety risks(RWS)
- The road operator has to help and change the standard road operation (PvB)
- It has to be proven that on this location no traffic jams will appear during the trial(RWS)

risks for project:

- Time risks(RWS & PvB)

A.3.7. Rijkswaterstaat traffic centre & Poort van Bunnik, Utrecht 13-06-2017

During the last meeting the almost final design is discussed. In the final design only merging work traffic was excluded, and this was already recommended by experts during this meeting. It is impossible to lower or higher the speed limits different from 90 and 70 km/h. The 90 km/h stage is created in this field trial since it is unnecessary. The speed limit will therefore change for 70 to 90 to 70 again.

The road operators will be informed, and it is possible for the researcher to observe both the initial situation of work zone 1 and the test night of work zone 2 and 3. Observations will be done in the traffic management centre.

The PCMS has to be deployed by the researcher or an other BAM employee since the traffic operating centre has no time for this.

The field trial is approved by the road authority.

B

Design questionnaire

B.1. Questions

Informatie bij wegwerkzaamheden

Beste Meneer/Mevrouw,

Voor mijn onderzoek naar het te hard rijden bij werkzaamheden werk ik aan een nieuwe manier van informatie voorziening bij werkzaamheden. Ik zou u daarom 5 korte vragen willen stellen over welke tekst u het meest begrijpelijk lijkt. De enquete bestaat uit 1 open vraag en 4 multiplechoice (2 of 3 keuzes) vragen.

met vriendelijke groet,

Marit Reinders
M.Reinders@student.tudelft.nl

*Required

1. **Als ik deze tekst tegen kom op de snelweg snap ik wel/niet wat het betekent? Leg uit.** *

Kies de meest begrijpelijke tekst

Van de onderstaande vragen zou ik graag willen dat u de voor u meest begrijpelijke tekst kiest, mocht u deze tegenkomen op de snelweg.

2. **Deze tekst geeft voor mij kort en duidelijk weer wat er bedoeld wordt:** *
Mark only one oval.

( ) NU plaatsen afzetting

( ) Plaatsen afzetting

( ) Other:

3. **Deze tekst geeft voor mij kort en duidelijk weer wat er bedoeld wordt:** *

Mark only one oval.

( ) Korte tijd geen werk

( ) Momenteel geen werk

( ) Tijdelijk geen werk

( ) Other:

4. **Deze tekst geeft voor mij kort en duidelijk weer wat er bedoeld wordt:** *

Mark only one oval.

( ) Werk aan vangrail

( ) Vangrail onderhoud

( ) Other:

5. **Deze tekst geeft voor mij kort en duidelijk weer wat er bedoeld wordt:** *

Mark only one oval.

( ) Opruimen afzetting

( ) Verwijderen afzetting

( ) Weghalen afzetting

( ) Other:

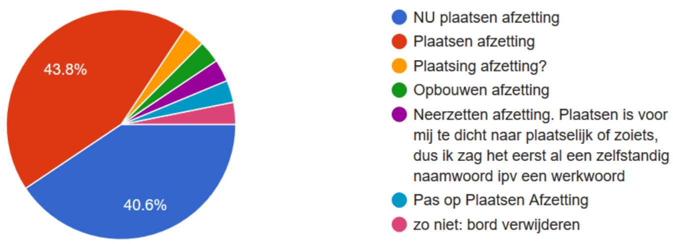
Dank u wel

Dank u wel voor het invullen van de enquête! Voor vragen kunt u terecht bij mij, Marit Reinders.
M.Reinders@student.tudelft.nl

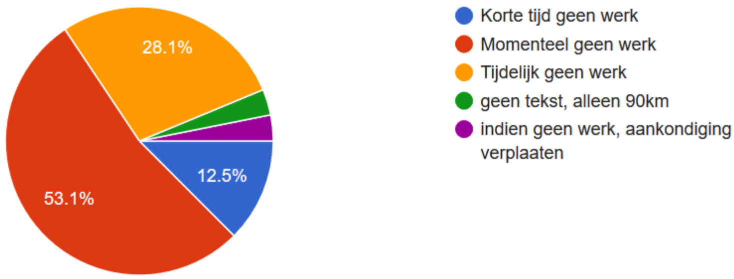
B.2. Responses

Table B.1: Raw output question 1 of detailed design questionnaire

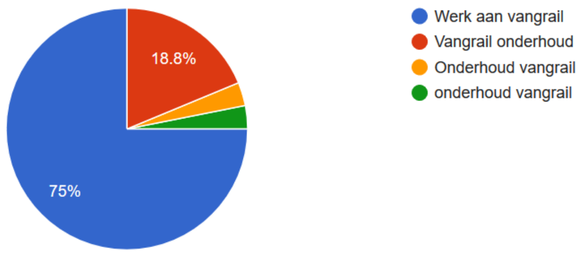
Question 1: Als ik deze tekst tegen kom op de snelweg snap ik wel/niet wat het betekent? Leg uit.
Wel. Werkverkeer voegt uit op onverwachte momenten.
Ja dat er als op een andere rijstrook werkzaamheden zijn dat de auto's die daar vandaan komen gaan invoegen
Werkverkeer voegt in
Niet. In ieder geval moet ik het eerst en lezen en dan nog verwerken omdat de tekst niet eenduidig is. Dan ben ik er met de auto allang voorbij
Wel wat het betekent maar niet wat de consequenties zijn
Wel, er rijdt op het moment werkverkeer de weg af
Niet duidelijk. Wat zijn de consequenties dat werkverkeer gaat uitvoegen en bedoel je met nu per direct of nu gaande over de komende x kilometers?
niet, hoezo uitvoegend, ik denk werk in uitvoering
niet, is het gevaar dat er werkverkeer op de uitvoegstrook staat en dat er daa dus werkzaamheden zijn of dat er er heel traag werkverkeer aan het uitvoegen is?
Ja. Het is een waarschuwing dat er (langzamer)werkvervoer op de rijbaan kan verschijnen.
Ik denk dat ik snap wat het betekent. Ik vind alleen 'NU' verwarrend in deze.
WEL
Er wordt hier aan de weg gewerkt en het verkeer dat hiervoor zaken en of mensen aanvoert moet vanaf hier uitvoegen en gaat dus langzamer rijden
Er kan werkverkeer langzamer rijden om uit te voegen
Dit snap ik wel.
Werkverkeer kan snelheid minderen om uit te voegen. Dus daarvoor oppassen
Niet echt meteen, (meer omdat jij meer hebt uitgelegd ;). Ik zou het niet zo snel koppelen aan lagere snelheden
Nee, werk verkeer dat uitvoegt? Maar waarom je daarvoor moet opletten snap ik niet
Ik snap het, werkzaamheden zijn nu en mogelijk is er uitvoegend werkverkeer.
Ja
Niet. Nu? Twee aanduidingen: pas op en oase op werkzaamheden
Wel. Maar vind het niet erg duidelijk.
Vanaf dit moment kan er (werk-)verkeer uitvoegen
Er wordt gewerkt aan de weg. Bij deze werkzaamheden kunnen evt werkauto's uitvoegen van de normale rijbaan naar de werkplek
ja, er kan op dit moment uitvoegend werkverkeer zijn
Opletten dat er werkverkeer op de rijbaan kan invoegen.
er is nu uitvoegend werkverkeer
lijkt me duidelijk
snap ik wel. Er kan werkverkeer op de autobaan komen .
Ja, het werkverkeer rijdt de weg op en dit vergt oplettendheid
Kans dat er werkverkeer de weg op komt rijden
Dat er op dit moment echt gewerkt wordt



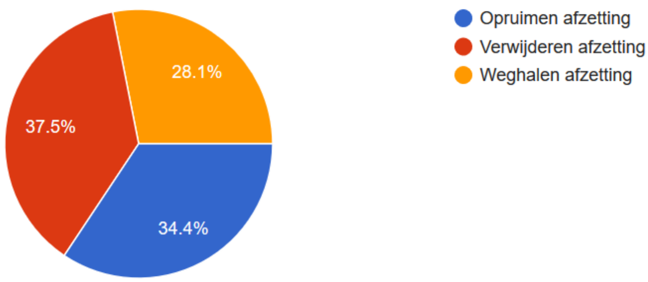
(a) Comprehensibility of time indication



(b) Phrasing 'No visible work activity'



(c) Phrasing 'construction work crash barrier'



(d) Phrasing 'removal of traffic measures'

Figure B.1: Raw output of detailed design questionnaire

C

Field trial deployment

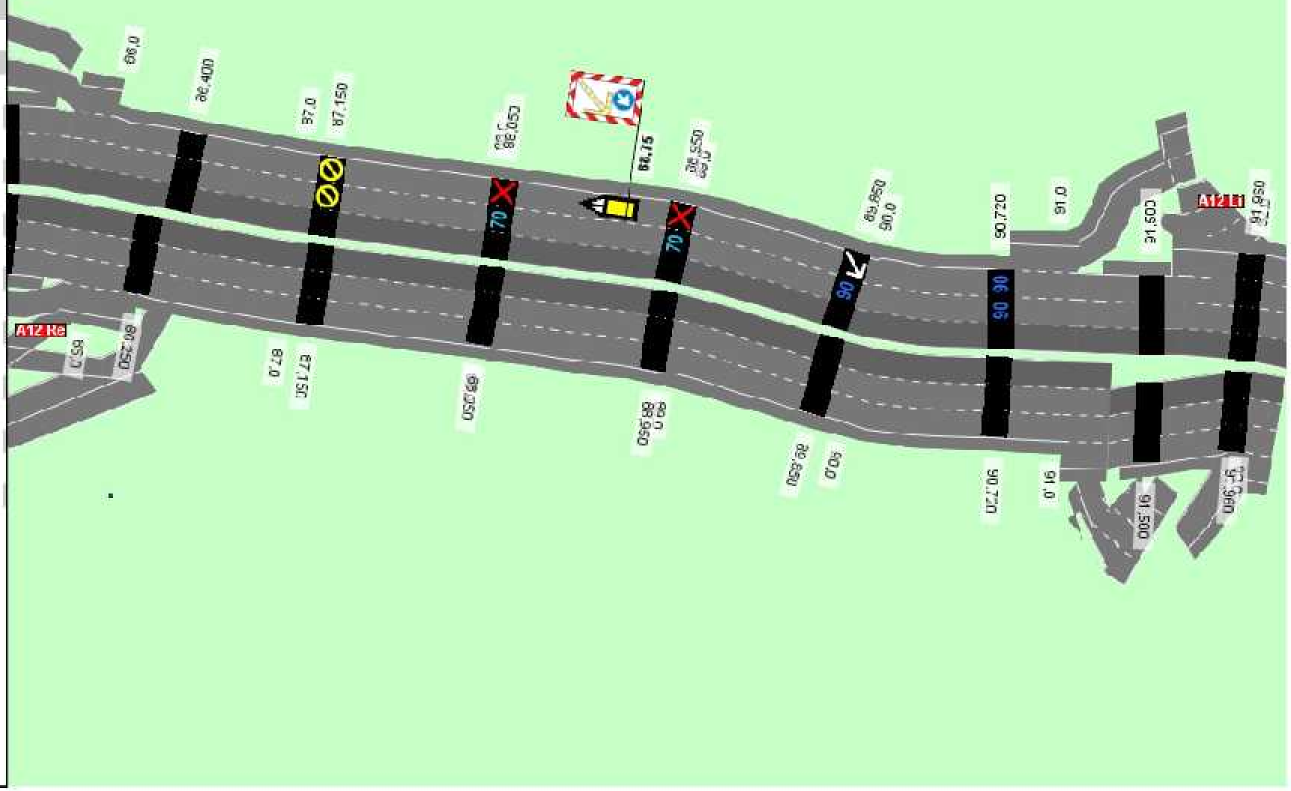
This appendix provides all the QSHE documents connected to the field test. The SPIN Requests approved by Rijkswaterstaat, the risk register used to mitigate all risks involving the field test and the deployment plan used to instruct the crew.

C.1. SPIN Requests

Schematische kaart maatregel MN-Z-240826

21.06.2017, 20:00 t/m 22.06.2017, 05:00

Aanvraagnummer	
MN-Z-240826	
Maatregel ID	
285529	
Locatie	
A12 Li 89,850 - A12 Li 87,150 Arnhem - Utrecht Veenendaal-West - Oudenhorst	
Verkeershinderklasse	
1 (geen file)	
Wegbeheerder	
MN-Z	



Schematische kaart maatregel MN-Z-247392	21.06.2017, 20:15 t/m 22.06.2017, 05:00

Aanvraagnummer

MN-Z-247392

Maatregel ID

293371

Locatie

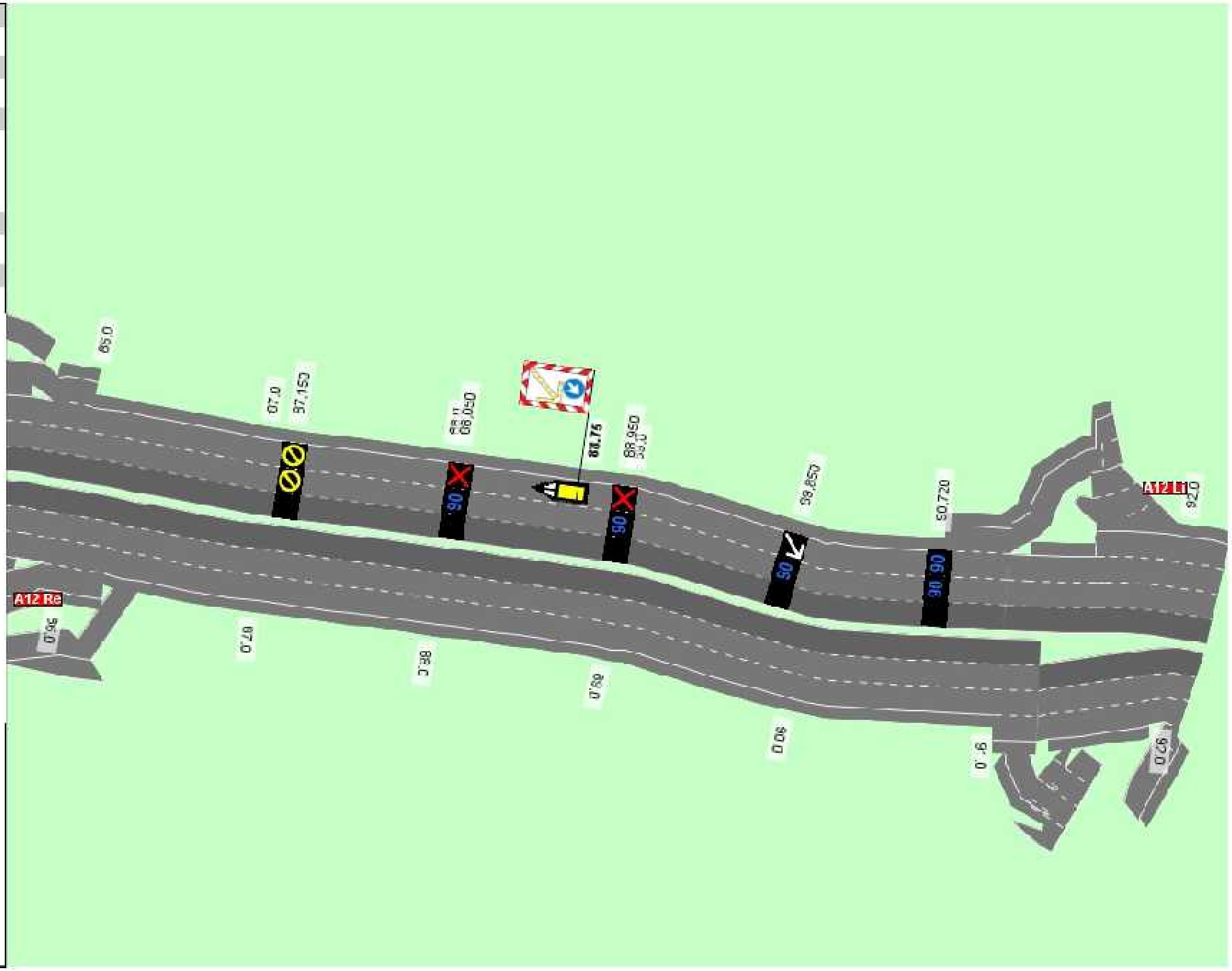
A12 Li 89,850 - A12 Li 87,150
Arnhem - Utrecht
Veenendaal-West - Oudenhorst

Verkeershinderklasse

1 (geen file)

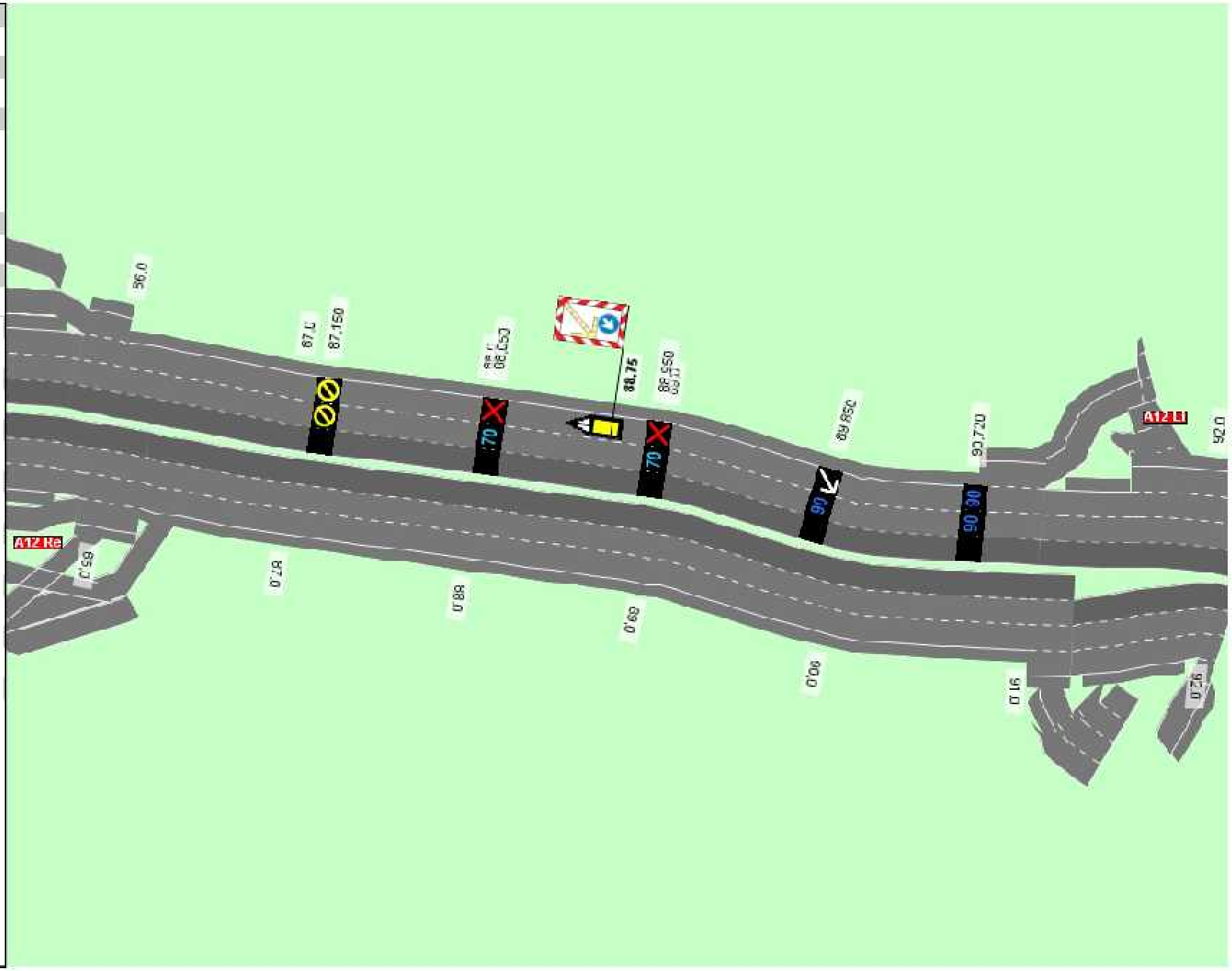
Wegbeheerder

MN-Z



Schematische kaart maatregel MN-Z-247393	21.06.2017, 20:30 t/m 22.06.2017, 05:00

Aanvraagnummer
MN-Z-247393
Maatregel ID
293372
Locatie
A12 Li 89,850 - A12 Li 87,150 Arnhem - Utrecht Veenendaal-West - Oudenhorst
Verkeershinderklasse
1 (geen file)
Wegbeheerder
MN-Z



C.2. Risk register

RISK REGISTER

Date: **12-6-2017** Version: **0.3**

author: **Marit Reinders** Phase: **Planning and Construction**

Reviewer: approver:

"acceptable "

"undesirable, acceptable for low Tender Management"

"unacceptable, additional mitigation compulsory"

Risk Description					Initial S-Q				Control meassure	Residual S-Q			
line #	**Risk**	**Cause**	**Effect**	**Risk Type**	**P**	**Th**	**VVU**	**R**	**p=preventive; c=corrective**	**P**	**Th**	**VVU**	**R**
1	stationary traffic	high traffic volume on A12 traffic incident	contaminated speed data	experiment control	2	4	3	14	p1: study intensity in normal stiuation 3 weeks befor test c1: exclude contaminated data	1	3	3	6
2	loop detectors mallfunctioning	out of scope (h.o.s Monica)	lack of speed data	experiment control	3	4	1	15	p1: check loop detectors data 3 weeks before test p2: communication with subcontractor	2	3	1	8
4	Incident with personal injury	traffic related incident work related incident	personal injury investigation into involvement of test	safety	1	1	5	6	p1: agreement with road authority p2: worked-out incident scenario c1: Evaluation of incident	1	1	5	6
5	failure of dynamic message car	out of scope(h.o.s. IVT)	no complete variable system	system control	3	4	1	15	p1: Test variable message car before test	1	4	1	5
6	Turbulence in initial situation meassurement	high traffic volume on A12 high traffic volume on on-ramp	uncomparable speed data	experiment control	2	4	2	12	p1: study intensity in normal situation 3 weeks before test c1: exclude results	1	3	2	5
7	bad weather conditions	out of scope	contaminated speed data	experiment control safety	2	4	1	10	p1: june so relatively good weather c1: exclude results	2	3	1	8
8	local discontinuities	overdue maintainance	contaminated speed data traffic related incident	experiment control safety	1	4	3	7	p1: last maintainance week, lowest chance	1	4	3	7
9	Enforcement during experiment	lack of communication between involved parties	contaminated speed data legal complications	experiment control legal	1	5	2	7	p1: agreement with road authority p2: agreement with enforcement authorities	1	4	3	7
10	deviation of work plan/work schedule	unexpected work conditions	deviation of SPIN assignments	experiment control	3	3	1	12	p1: agreement with foreman of (sub)contractors p2: presence during work preperation meeting(Safety Toolbox meeting)	2	2	1	6
11	communication failure in communication chain	inexpierence in system	deviation in system set-up	experiment control system control	4	4	1	20	p1: preparation with foremand of (sub)contractors p2: first the initial situation night p3: preparation with Traffic Center	2	4	1	10

C.3. Deployment plan

BAM Infraconsult bv

Memo

Aan	Hamering, Bert; Brinkman, Henk-Jan
Kopie aan	Lafranceschina, Rino van der Heijden, Harry Borsje, Johan Baelde, Frank
Van	Marit Reinders
Telefoon	
E-mail	
Datum	19 juni 2017
Referentie	BIC-17-M-00001- 1 van 3
Onderwerp	**Werkinstructie**

Beste collega ,

In opdracht van BAM Infraconsult onderzoek ik hoe we bij onze werkzaamheden verkeersdeelnemers beter kunnen ‘afremmen’. Het te hard rijden bij werkzaamheden is voor jullie waarschijnlijk ook een bekend fenomeen. Ik vraag jullie medewerking om het een avond ‘anders’ te doen. We gaan een experiment uitvoeren **tijdens werkvak verlagen geleiderail (Veenendaal west) op 20 & 21 juni.** Op 20 juni is er sprake van een zogenaamde ‘nul-meting’ waarin we niets anders doen. Ik zou dan alleen van de fases in de onderstaande tabel willen weten wanneer ze plaatstvinden zodat ik de metingen kan vergelijken. De nacht van woensdag 21 op 22 is de daadwerkelijke test. De avonden worden geëvalueerd middels snelheidsmetingen, maar ook jullie feedback is gewenst.

Het ontwerp van de verkeersmaatregelen is gebaseerd op de wegsituatie vanuit de weggebruiker Door naar de weggebruikers te communiceren, en bij een leeg werk vak een hogere snelheid toe te laten, hopen we resultaat te boeken in de vorm van minder te hard rijdende verkeersdeelnemers. Een lagere maximum snelheid zou gepast zijn bij bepaalde werk fases (zoals het plaatsen van verkeersmaatregelen), helaas is dat uit dit experiment gevallen.

Alvast bedankt voor de medewerking.
Marit Reinders

Voor schema z.o.z.

BAM Infraconsult bv

Memo

De actie(communicatie) lijst van **dinsdag 20 juni** nacht is het volgende:"

Fase	Tijd	Actie	Actie houder	meldwerknummer	SPIN
Plaatsen afzetting	21:00	**Bel Verkeerscentrale** Bel/app Marit			
Niemand in werk vak	**Minstens 15 min.**	Bel/app Marit			
Invoegend werkverkeer	**Niet voor 21:30**	Bel/app Marit			
Normaal werk, geen extra bewegingen		Bel/app Marit			
Niemand in werk vak		Bel/app Marit			
Weghalen afzetting		Bel/app Marit Klaar? **Bel Verkeerscentrale**			

De actie(communicatie) lijst van **woensdag 21 juni** nacht is het volgende:"

Fase	Tijd	Actie	Actie houder	meldwerknummer	SPIN
Plaatsen afzetting	21:00	**Bel Verkeerscentrale** Bel Marit		**240826**	**285529**
Niemand in werk vak	**Minstens 15 min.**	**Bel. Verkeerscentrale** Bel Marit		**247392**	**293371**
Invoegend werkverkeer	**Niet voor 21:30**	**Bel. Verkeerscentrale** Bel Marit		**247393**	**293372**
Normaal werk, geen extra bewegingen		Bel Marit			
Niemand in werk vak		Bel Marit			
Weghalen afzetting		Bel Marit Klaar? **Bel Verkeerscentrale**		**afmelden**	

C.4. Observations 20-06-2017 work zone 1

Table C.1: Observations work zone 1

Time	Location	Observation
20:02		Placement traffic measures
20:55	77,0	work vehicles
20:55	76,6	Activity
21:33	70,6	Police
22:00	77,5	Police
22:01	76,4	Police
22:03	77,0	Police
22:04	77,0	merging work traffic
22:08	77,8	merging work traffic
22:26		traffic jam
22:26	77,2	merging work traffic
22:39	76,9	merging work traffic

C.5. Observations 21-06-2017 work zone 2

Table C.2: Observations work zone 2

Time	Location	Observation
20:03		Red crosses
20:06	78	Action car
	77.5	Police
20:12	77.7	Action car
20:21	76.2	Placement of traffic measures
20:23		Empty work zone except for police and work vehicle at 77.7
20:25	77.5	merging work traffic
20:31	77.2	work
21:46	77	larger work vehicle
22:25	77	Very busy, plus minus jam
23:54	76.6	work
01:17	76.6+	work
02:33	75.9	work with large vehicles
02:48	77	large activity in work zone
02:58	76.6	police
03:11	76.2	merging work traffic
03:14	76.6	removal of traffic measures
03:18	77.2	almost gone, coupling of action car to vehicle
03:25	77.8	shock absorber-truck
03:29	77.9	action car fold up on emergency lane
03:29	77.9	away via emergency lane

C.6. Observations 21-06-2017 work zone 3

Table C.3: Observations work zone 3

Time	Location	Observation
20:53		Placement measures
21:09		No work
21:29		Start work(call)
21:36	88.9	merging work traffic
21:45	88.9+	small work vehicles
22:03	88.2	small work vehicles
22:03	88.9+	Larger work vehicles
22:25	88.2	Larger work vehicles
23:29	88.2	shock absorber truck
23:45	88.2	shock absorber truck in work zone
0:38	88.9	large work vehicle
01:18	88.2+	small work vehicles
03:53	88.9	shock absorber truck merging in work zone
04:00	88.9	merging work traffic
04:08	91.4	driver driving backwards on emergency lane
04:17	88.2	work crew leaves
04:19		removal of traffic measures
04:27	89	traffic measures removed

D
Mann-Whitney results and sensitivity

The one on one comparison using the Mann-Whitney U test resulted in inconclusive results. This is shown in this appendix. Also the sensitivity of the results are shown, yet, they are not very sensitive since little factors are included in this comparison.

D.1. Results using Mann Whitney U test

The results using the Mann-Whitney U test lead to inconclusive results in both the effect of the PCMS and the effect on the text of the PCMS.

D.1.1. Effect of the PCMS

Researching the effect of the PCMS the moment in which the dynamic speed limit was set to 90km/h should be ignored and this time is filtered out of the dataset. The fourth flow category is analysed and work zone 2 and 3 are compared in Figure D.1.

Three major differences are shown by the box plots figure. The first effect is somewhat unexpected, a large speed difference at point 5. It seems the on-ramp has a much bigger effect in the work zone situation than in the non-work zone situation. In the road consistency test, point 5 does not stand out any more in the fourth flow category. In the work zone situation because of the one-lane situation on the on-ramp, the effect is much larger.

Another unexpected difference is the increase of speed in the activity area of work zone 2. Based on the found literature it is expected that in a active work zone drivers are less likely to speed. In work zone 2 from point 5 to point 6 the speed increases, to decrease again at point 7. It is an effect which is not shown in the work zone 3 of Veenendaal and is also likely to be caused by the on-ramp. It seems drivers find their speed inappropriately low and increase it a bit.

As expected, the median speed in work zone 3 at the point where the PCMS is situated (point 2) is lower. If drivers want to read the PCMS, their speed is likely to decrease because of the increase in workload. This effect seems to be temporary because at point 3 it is not visible anymore. If drivers would read the message, which explains the work zone, then a decrease of speed in the work zone is expected as well. The speed in work zone 3 at point 6 and 7 is indeed lower which is enhanced by the lower speed of work zone 2 in point 5.

The statistical Mann-Whitney U test is used to see if these differences are significant. The hypothesis of the test is if the median speed in work zone 3 is less than the median speed in work zone 2. A one-tailed test for a specific direction. The result of the third and fourth flow category is shown in Table D.1.

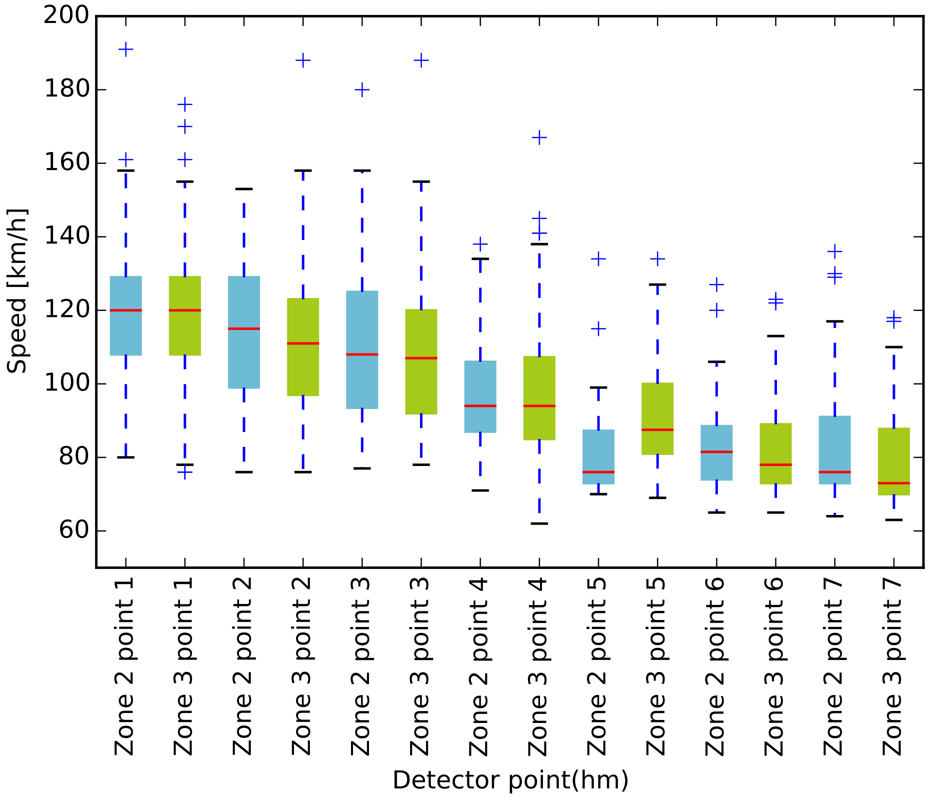


Figure D.1: Box-plot with median flow in each point for flow category 3 and 4 in each work zone

It is shown that in Point 2 in flow category the speed is indeed 'less' yet not significant with the significance level of 95%. In point 7 of WZ 3, the speed is significantly less than in point 7 of WZ2. The difference at point 7 is probably due to the exact location of the activity since in WZ 2 the work already passed. Because of all the factors in between point 2 and the activity area it is highly unlikely the PCMS affected this difference.

Flow category 3 is added to the table because in this flow category the speed difference at point 2 is significantly different. And although this category was marked as incomparable, in point 2 specifically category 3 is comparable in terms of road consistency. Another indication that in this point the PCMS influenced a speed decrease. A point of discussion is whether the effect of the on-ramp at point 1 in work zone 3 did not become larger due to the higher flow. The influence of the on-ramp is however unexpected because it is not visible in the road consistency and the road has 2 open lanes.

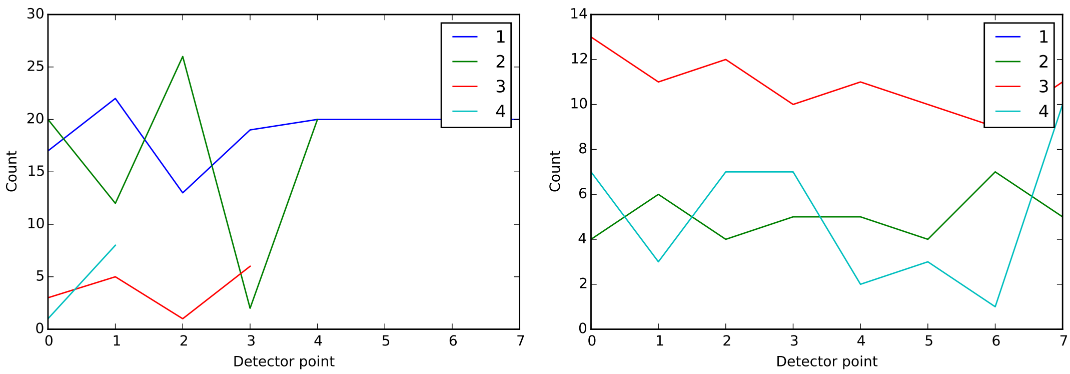
Table D.1: P-value of one-tailed Mann-Whitney U test with hypothesis: Speed in WZ3 is less than WZ 2 in each point

Point	Flow category 3	Flow category 4
1	0,217	0,416
2	0,001	0,056
3	0,157	0,293
4	0,602	0,407
5	1,000	1,000
6	0,996	0,261
7	0,001	0,010

In conclusion, there are indications the PCMS affected a speed decrease at point 2 of work zone 3. It is however not significant and there are too many factors which cannot be excluded influencing the speed to conclude the PCMS caused a decrease of the traffic speed.

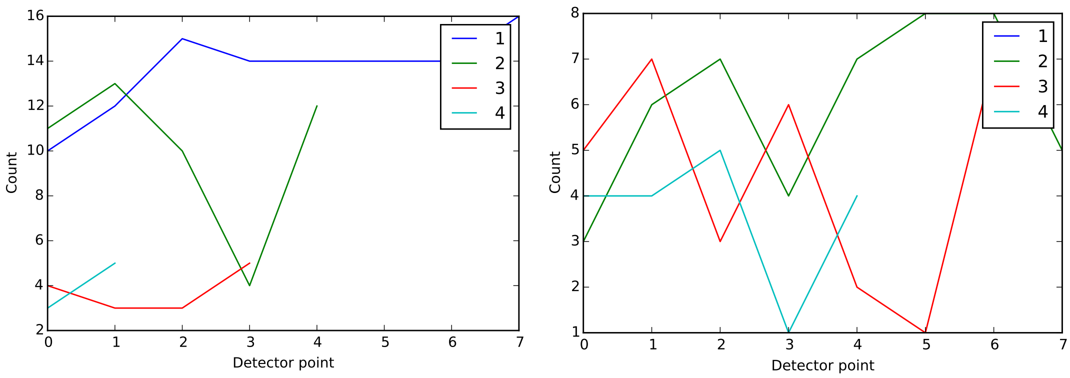
D.1.2. Effect of the text

From the conclusions on the effect of the PCMS, it can be concluded that it is unlikely the text on the PCMS influences speed measurements. Since no conclusions on the effect of the PCMS are possible. If an effect of the text can be found, then it should be sought in the difference between the phases 'placement of traffic measures' and 'removal of traffic measures' of work zone 2 and work zone 3. These phases can be compared to phase 3 'work on the crash barrier' in the matching work zone. If there are large differences in the differences between work zone 2 and work zone 3, this may indicate an effect of the text on the PCMS. The number of observations of those phases and work zones can be found in Figure D.2



(a) Number of observations in each flow category in Phase 1 'Placement traffic measures' Work zone 2

(b) Number of observations in each flow category in Phase 4 'Removal traffic measures' Work zone 2



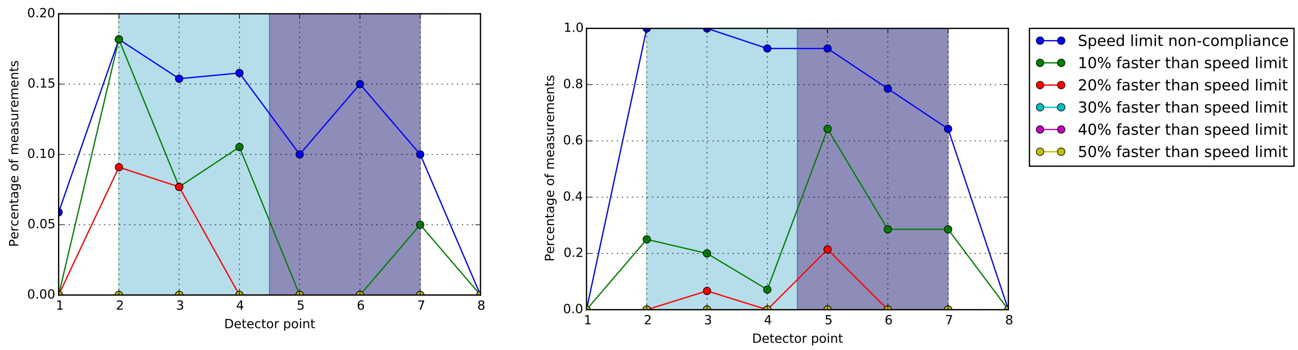
(c) Number of observations in each flow category in Phase 1 'Placement traffic measures' Work zone 3

(d) Number of observations in each flow category in Phase 4 'Removal traffic measures' Work zone 3

Figure D.2: Number of observations in each flow category per detector point in WZ2 and WZ3 in phases 1 and 4

The figures per work zone per phase show that in these small time frames not many observations are counted. Especially in phase 4, which is late in the night, the number of observations is around ten per point. Ten measurements per point are far too few to draw significant conclusions. In phase 1 of work zone 2 and 3 the first flow category has enough measurements. The speed limit compliance of phase 1 in work zone 2 and 3 is shown in Figure D.3.

Figure D.3a shows the speed limit compliance in work zone 2 phase 1 is exceptionally high and lays around 85%. In work zone 2 no PCMS was placed, and this unexpected high-speed limit compliance cannot reasonably be due to other factors than very high traffic volume or enforcement. Both elements, the categorisation of the traffic flow and enforcement will be elaborated on in the sensitivity of the data



(a) Speed limit non-compliance of phase 1 work zone 2

(b) Speed limit non-compliance of phase 1 work zone 3

Figure D.3: Speed limit non-compliance of phase 1 'placement of traffic meassures' per point in work zone 2 and 3

analysis in Section D.2. On the text of the PCMS, just like the PCMS itself, no significant conclusions can be drawn.

D.2. Sensitivity analysis

In Sections D.1 and 6.3 the results of the Mann-Whitney U test analysis is presented. Due to uncontrolled factors influencing the field trial, many steps had to be taken to conclude on the effect of the new system. Especially the flow categorisation influences the data analysis in such a way that the sensitivity for this categorisation should be studied. Two new methods for flow categorisation are proposed in this section and their effect on the analysis and results is presented.

Then the uncontrolled operating environment of the field trial influences the results. The effect of factors incorporated in the Risk Register C.2 of the field trial is also studied in this section.

D.2.1. Flow categories

In the data analysis especially flow category 1 and flow category 4 were important. Flow category 1 is used to analyse the effect of the dynamic speed limit. Flow category 4 is used in studying the effect of the PCMS. These flow categories are changed to see if this would have a major impact on the data analysis.

If the lower boundary of flow category 1 is heightened from 600 veh/hour/lane to 1020 veh/hour/lane, this has a large effect on the number of observations in the first flow category. The number of observations in the category decreases from 878 to 270, and this is shown in Table D.2. In the first point of work zone 3, there is only one measurement of flow above 1020 veh/hour/lane. This low number of observations is because in this part of the work zone 2 lanes are opened. From point 5 on there are about 70 measurements in the new flow category 1. With this larger number of measurements the difference between the old and the new median speed disappears. This effect is shown in Figure D.4. In general the speed in the new flow category is somewhat lower, this is a logical result of the higher flow. Only at point 2, where the PCMS was located, this difference is not found.

The threshold of flow category 1 can also be lowered. The threshold is lowered to 420 veh/lane/hour and the number of observations in the category increases. This increase is shown in Table D.3 where the total number of observations increases from 878 to 1274. The difference in speed is less significant than that of the heightening of the threshold. The number of observations probably decreases the variation of the measurements. Only in the first three detector points a difference can be found, as expected the new speed is higher than the old speed. The speed difference is only visible in the V85 speed and is hardly visible in the speed median. It can be concluded the variation increases with lower flow. This is already made visible in comparing the boxplots of 6.9 and 6.10 in Chapter 7.

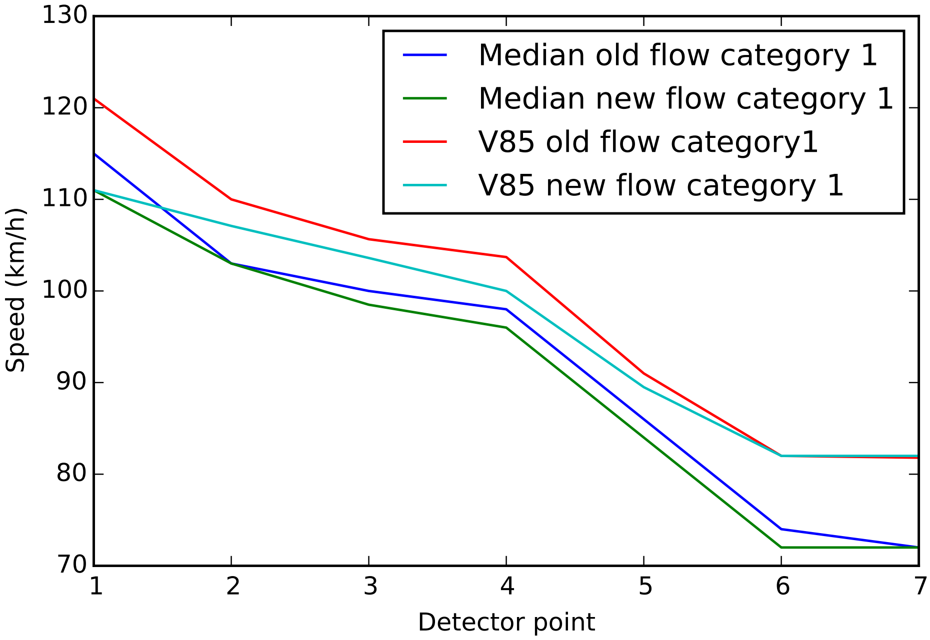


Figure D.4: Absolute median and V85 speed of flow category 1 in WZ3 when category boundary is heightened to 1020 veh/hour/lane

Table D.2: Overview of effect of increasing flow category 1 threshold to 1020 veh./hour/lane

Point	#observation >600	#observations >1020	Median >600	median >1020	V85 >600	V85 >1020
1	61	1	115	111	121	111
2	121	7	103	103	110	107,1
3	130	10	100	98,5	105,65	103,6
4	123	42	98	96	103,7	100
5	146	71	86	84	91	89,5
6	148	70	74	72	82	82
7	149	69	72	72	81,8	82
total	878	270	92,6	90,9	99,3	96,5

Table D.3: Overview of effect of decreasing flow category 1 threshold to 420 veh./hour/lane

Point	#observation >600	#observations >420	Median >600	median >420	V85 >600	V85 >420
1	61	158	115	112	121	121
2	121	201	103	104	110	114
3	130	201	100	100	105,65	108
4	123	161	98	98	103,7	104
5	146	185	86	86	91	91
6	148	184	74	75	82	83
7	149	184	72	73	81,8	81
total	878	1274	92,6	92,6	99,3	100,3

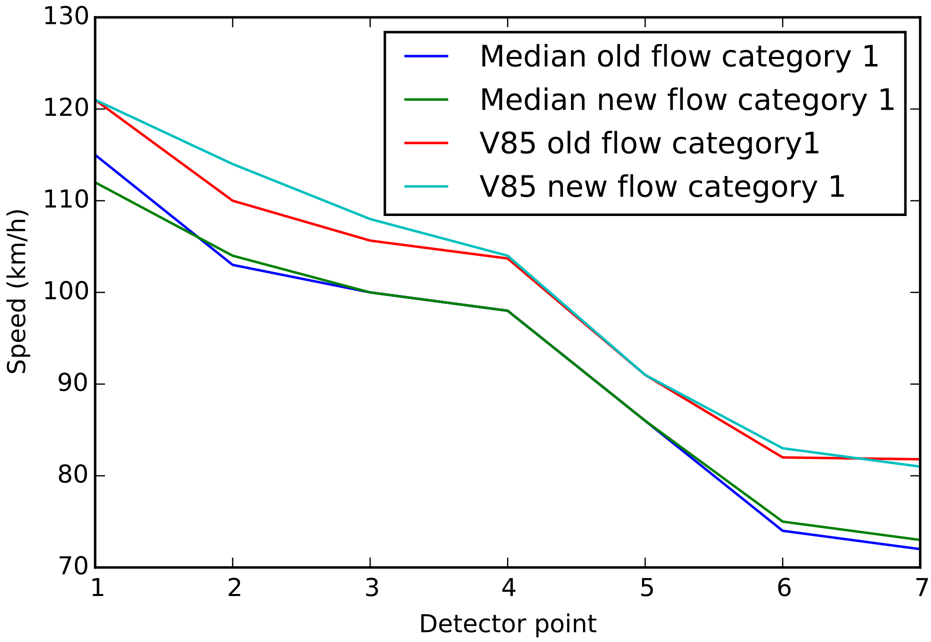
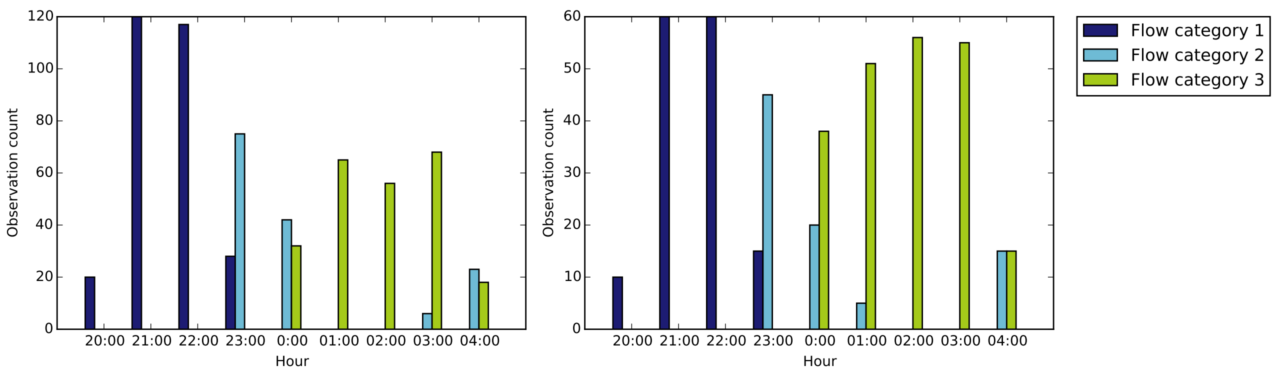


Figure D.5: Absolute median and V85 speed of flow category 1 in WZ3 when category boundary is lowered to 420/veh/hour/lane

D.2.2. Five-minute aggregation of data

Although traffic flow is a continuous variable, it is measured in a minute aggregated setting. In that manner, a flow profile like 120-240-60-120-120 is possible in a five-minute time frame. One can ask if the 240 didn't influence the 60 and so on since the data is only minute aggregated. What if the flow was 5 minute aggregated? The flow category count for work zone 3 points 2 and 6 is shown in Figure D.6.

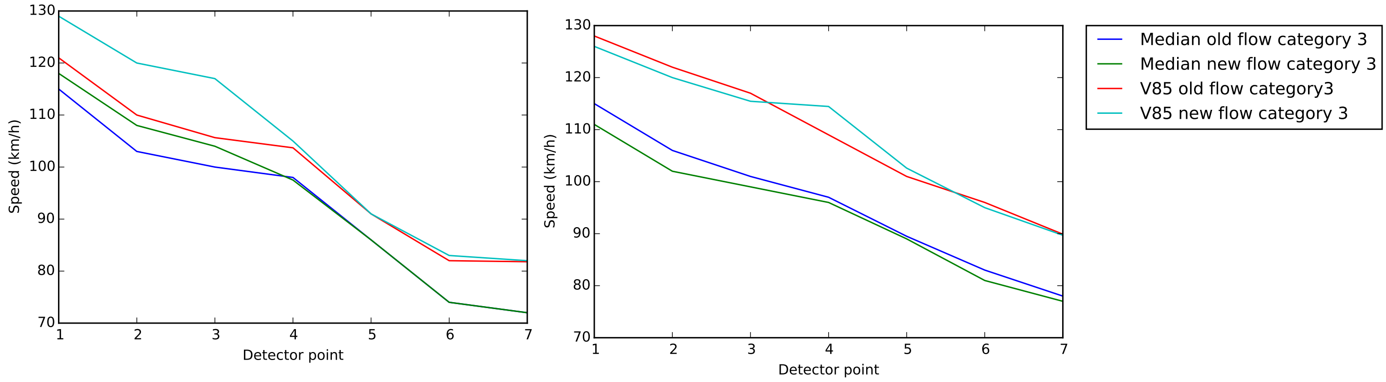


(a) Number of observations WZ3 Point 2

(b) Number of observations WZ3 Point 6

Figure D.6: Number of observations WZ3 in point 2 and 6 per flow category

What immediately stands out is flow category 4 falls out of the analysis. In work zone 3, flow category 4 can be found once between 02:25 and 02:29 in Point 1. The transition of the flow categories is more smooth than the minute aggregated profiles. There is an clear transition from the first flow category to the second and to the third, while at the end the second flow category appears again. This could be due to the fact that it already becomes more busy at 4, the intensive work in this last 30 minutes in which the traffic measures are removed or a combination of both. The effect is also visible in work zone 1 which was also dismissed around 04:30. In some points, the effect is already apparent in the second hour after midnight, so it is most likely influenced by the increasing traffic.



(a) Median and V85 speed WZ 3 new and old flow category 1

(b) Median and V85 speed WZ 3 new and old flow category 3

Figure D.7: Number of observations WZ3 in point 2 and 6 per flow category

The effect of the new flow categorisation method on the speed is shown in Figure D.7a and D.7b in which respectively flow category 1 and 3 are shown. In the first figure, large effects are shown. Many speed measurements from former flow category 2,3 and even 4 are added to the first flow category because their 5 minutes mean is above 600 veh/hour/point. The variation within this category increases, in the activity area, no significant changes can be found. In the third flow category, especially measurements from the 4th flow category are added. This addition has no significant effect on the speed, only in point 4 a significant increase can be found.

Table D.4: P-value of one-tailed Mann-Whitney U test with hypothesis: Speed in WZ 3 is less than WZ2 in each point with 5 minutes aggregated flow categories

Point	Flow category 1	Flow category 2	Flow category 3
1	0,744	0,677	0,387
2	0,016	0,072	0,010
3	0,733	0,020	0,128
4	0,884	0,082	0,584
5	1,000	1,000	1,000
6	1,000	1,000	1,000
7	0,000	0,000	0,000

Since the fourth and third flow category are merged into one third flow category in Table D.4, point 2 now does give a significant result. This is expected when looking back at Table D.1, however, it is important to remember flow category 3 tests negative on the road consistency test and was therefore excluded.

D.2.3. Enforcement

During the period that a police car was driving through the work zone, an effect on the whole traffic stream in the work zone can be expected. Because of this effect, all the data of the work zone of 5 minutes around a police observation is excluded. In work zone 2 an extreme case of enforcement was observed. The police car stood still in the work zones buffer area for 30 minutes. The data of the work zone during that time is also excluded. Table 6.1 provides an overview of all excluded measurements due to enforcement. There is a real possibility not all police enforcement were detected by the researcher. Therefore the sensitivity of the results for enforcement should be tested.

Since the most severe enforcement was seen in work zone 2, this work zone is used for the comparison of Mann-Whitney u test outcomes. The comparison between work zone 2 and work zone 3 is repeated with the enforcement filter. Although only significant conclusions could be drawn from the fourth flow category, the most severe effect of the filter is seen in flow category 1. This effect is shown in Table D.5. The difference between the p-values of the points within the category stay within the same order of magnitude of the p-value itself.

Table D.5: P-value of Mann-Whitney U test with hypothesis: Speed in WZ3 is less than WZ2 of flow category 1 in each point with and without enforcement filter

Point	Flow category 1 enforcement filter	Flow category 1 no filter	Difference
1	0,890	0,780	0,110
2	0,000	0,000	0,000
3	0,004	0,000	0,004
4	0,958	0,955	0,003
5	1,000	1,000	0,000
6	1,000	0,998	0,002
7	0,000	0,000	0,000

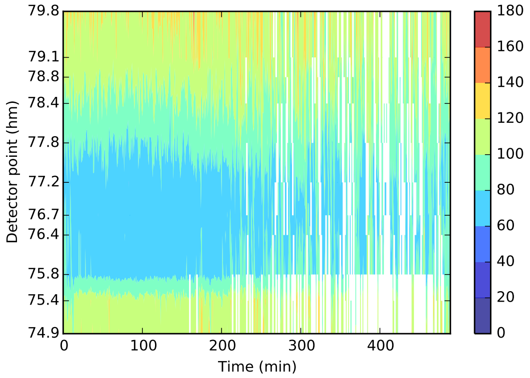
Conclusions on the effect of the PCMS are drawn from the fourth flow category. The new p-value of the 4th flow category is shown in Table D.6. No substantial differences are shown and the order of magnitude of the differences is smaller than that of the p-value itself. The enforcement filter does not affect the result of the test.

Table D.6: P-value of Mann-Whitney U test with hypothesis: Speed in WZ3 is less than WZ2 of flow category 4 in each point with and without enforcement filter

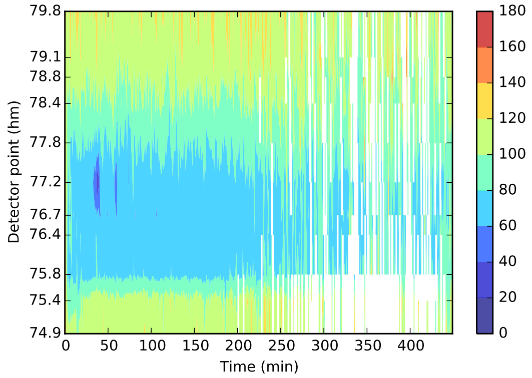
Point	Flow category 4 enforcement filter	Flow category 4 no filter	Difference
1	0,416	0,416	0,000
2	0,052	0,056	-0,004
3	0,293	0,293	0,000
4	0,454	0,407	0,046
5	1,000	1,000	0,000
6	0,261	0,261	0,000
7	0,010	0,010	0,000

D.2.4. Congestion

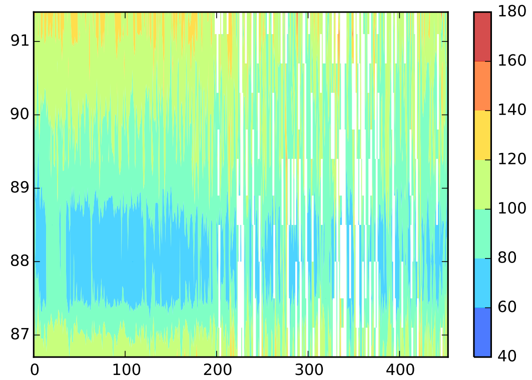
Congestion is mentioned in the risk register of Appendix C.2 as an experiment control risk. Using the speed contour plot, traffic jams can be identified. In work zone 2 shown in Figure D.8b a traffic jam is visible. The jam forms around the on-ramp on point 77,2. This specific point is left out the data analysis because of this on-ramp. Traffic jams create a capacity drop downstream of the jam. This drop can influence point 5 in the analysis. This is visible in the box plots, where around point 5 a low speed is visible. It is however unlikely the jam effects influence the outcomes since point 5 was already incomparable. Point 5 also gives a deficient speed in work zone 1 where no jam occurred, and the specific speed measurements of below 60km/h were left out of the analysis because point 77,2 was excluded.



(a) Speed contour of work zone 1 on Tuesday 20-06-2017 20:10 - Wednesday 22-06-2017 04:20



(b) Speed contour of work zone 2 on Wednesday 21-06-2017 20:00 - Thursday 22-06-2017 03:30



(c) Speed contour of work zone 3 on Wednesday 21-06-2017 20:50 - Thursday 22-06-2017 04:30

Figure D.8: Speed contour plots work zones

D.3. Road consistency Mann-Whitney U test

Table D.7: P-values of Mann-Whitney U test with the hypothesis: Speed in WZ 1/2(site Maarsbergen) is different(two-tailed) from speed in WZ 3 (site Veenendaal) during no work zone conditions on June 20th

	Test	00:00-04:00 20-6-2017				
Point	flow category	pValue	#observations WZ 1/2	#observations WZ 3	median WZ 1/2	median WZ 3
1	1	-	-	-	-	-
1	2	0.929	67	41	107	104
1	3	0.064	243	237	115	110
1	4	0.110	94	121	123	118
2	1	-	-	-	-	-
2	2	0.700	66	66	108	105.5
2	3	0.322	254	253	114	111
2	4	0.975	114	94	120	120
3	1	-	-	-	-	-
3	2	0.936	68	61	106.5	105
3	3	0.665	257	248	113	111
3	4	0.595	113	99	120	123
4	1	-	-	-	-	-
4	2	0.436	61	65	106	109
4	3	0.666	264	268	113	111
4	4	0.629	108	112	122	122
5	1	-	-	-	-	-
5	2	0.805	74	59	108	110
5	3	0.093	245	277	110	114.5
5	4	0.069	103	112	120	125
6	1	-	-	-	-	-
6	2	0.814	70	53	109	107
6	3	0.896	253	269	113	113
6	4	0.522	107	123	122	120
7	1	-	-	-	-	-
7	2	0.387	74	59	109	108
7	3	0.579	251	253	114	115
7	4	0.699	110	122	123	123

Table D.8: P-values of Mann-Whitney U test with the hypothesis: Speed in WZ 1/2(site Maarsbergen) is different(two-tailed) from speed in WZ 3 (site Veenendaal) during no work zone conditions on May 25th

Point	Test flow category	pValue2	#observations WZ 1/2	#observations WZ 3	median WZ 1/2	median WZ 3
		21:00 24-05-2107 - 04:00 25-05-2017				
1	1	0.004	141	86	115	112.5
1	2	0.003	274	280	119	116
1	3	0.137	313	330	125	123
1	4	0.314	114	137	127	125
2	1	0.001	137	130	114	111.5
2	2	0.213	294	284	119	117
2	3	0.285	299	308	124	122.5
2	4	0.559	108	122	127	127
3	1	0.362	142	130	114	113
3	2	0.731	292	282	118	118
3	3	0.622	289	302	124	122.5
3	4	0.170	118	120	125	129
4	1	0.505	136	129	114	116
4	2	0.147	296	297	118	119
4	3	0.075	280	282	123	126.5
4	4	0.072	104	122	123	128
5	1	0.000	174	133	114	118
5	2	0.004	279	290	118	120
5	3	0.077	280	296	123	126
5	4	0.154	109	112	127	129
6	1	0.215	181	135	115	116
6	2	0.073	264	282	119.5	120
6	3	0.402	281	306	123	125
6	4	0.464	99	118	125	129
7	1	0.326	171	136	115	116.5
7	2	0.561	275	277	120	120
7	3	0.157	275	308	124	127
7	4	0.699	103	116	129	129

Table D.9: P-values of Mann-Whitney U test with the hypothesis: Speed in WZ 1/2(site Maarsbergen) is different(two-tailed) from speed in WZ 3 (site Veenendaal) during no work zone conditions on May 4th

	Test	21:00 03-05-2107 - 04:00 04-05-2017				
Point	flow category	pValue5	#observations WZ 1/2	#observations WZ 3	median WZ 1/2	median WZ 3
1	1	0.602	88	38	114	113.5
1	2	0.407	228	221	115	114
1	3	0.258	352	373	120	118
1	4	0.050	144	156	123	120
2	1	0.128	88	80	113.5	112
2	2	0.601	230	225	114.5	114
2	3	0.351	352	345	119	118
2	4	0.949	157	132	125	123
3	1	0.442	89	85	114	113
3	2	0.935	221	211	115	114
3	3	0.742	356	344	118	118
3	4	0.706	142	135	123	123
4	1	0.224	93	85	114	114
4	2	0.009	235	230	115	118
4	3	0.179	345	331	117	120
4	4	0.173	150	133	122	127
5	1	0.001	98	74	112	115
5	2	0.000	243	241	114	117
5	3	0.170	338	351	117	121
5	4	0.968	131	156	122	123
6	1	0.181	95	83	114	115
6	2	0.696	252	225	115	115
6	3	0.039	321	351	118	121
6	4	0.421	127	154	123	124
7	1	0.466	112	80	115	114
7	2	0.624	234	232	116.5	116.5
7	3	0.842	319	350	121	121
7	4	0.457	128	155	125	125

E

MLRM output and diagnostics

E.1. Model output

E.1.1. PCMS

Table E.1: MLRM outcome pcms

	Estimate	SE	tStat	pValue
(Intercept)	121.42	0.28823	421.26	0
flow	-0.0083675	0.00026471	-31.61	8.9849e-212
truck	-19.771	0.72602	-27.231	4.364e-159
enforcement	0.96175	0.42416	2.2674	0.023379
pcms	-1.2494	0.33322	-3.7496	0.00017785
monramp	-11.892	0.48073	-24.738	3.1375e-13 2
vonramp	-2.2681	0.41703	-5.4387	5.4594e-08
activity	-3.4804	0.56001	-6.2148	5.2858e-10
pointmdl_2	-6.2575	0.32522	-19.241	1.9722e-81
pointmdl_3	-11.673	0.33245	-35.11	1.0003e-258
pointmdl_4	-18.161	0.3565	-50.943	0
pointmdl_5	-25.182	0.46337	-54.346	0
pointmdl_6	-30.562	0.67104	-45.544	0
pointmdl_7	-35.631	0.41476	-85.909	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.2. PCMS_0

Table E.2: MLRM outcome pcms_0

	Estimate	SE	tStat	pValue
(Intercept)	121.39	0.29066	417.64	0
flow	-0.008354	0.00026474	-31.555	4.5315e-211
truck	-19.778	0.72605	-27.241	3.4032e-159
enforcement	1.0458	0.42334	2.4705	0.013505
pcms_0	-1.9195	0.53402	-3.5944	0.00032622
monramp	-11.348	0.4583	-24.761	1.8259e-132
vonramp	-2.2051	0.4305	-5.1222	3.0614e-07
activity	-3.7171	0.55641	-6.6805	2.4725e-11
pointmdl_2	-6.0398	0.3562	-16.956	7.7312e-64
pointmdl_3	-11.988	0.30935	-38.753	6.5542e-312
pointmdl_4	-18.473	0.33019	-55.946	0
pointmdl_5	-25.616	0.43105	-59.427	0
pointmdl_6	-30.619	0.66962	-45.726	0
pointmdl_7	-35.632	0.41527	-85.804	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.3. PCMS_1

Table E.3: MLRM outcome pcms_1

	Estimate	SE	tStat	pValue
(Intercept)	121.38	0.2946	411.99	0
flow	-0.0083464	0.00026482	-31.517	1.4027e-210
truck	-19.763	0.72615	-27.216	6.4983e-159
enforcement	1.0242	0.42353	2.4182	0.015611
pcms_1	-1.6088	0.50374	-3.1936	0.0014081
monramp	-11.347	0.45835	-24.757	2.0171e-132
vonramp	-2.1663	0.45373	-4.7744	1.8212e-06
activity	-3.7171	0.55647	-17.355	9.2575e-67
pointmdl_3	-11.734	0.33398	-35.133	4.7935e-259
pointmdl_4	-18.461	0.33328	-55.392	0
pointmdl_5	-25.606	0.43328	-59.098	0
pointmdl_6	-30.61	0.67107	-45.614	0
pointmdl_7	-35.622	0.41756	-85.31	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.4. PCMS_2

Table E.4: MLRM outcome pcms_2

	Estimate	SE	tStat	pValue
(Intercept)	121.42	0.29253	415.06	0
flow	-0.0083559	0.00026478	-31.557	4.2377e-211
truck	-19.768	0.72617	-27.223	5.4071e-159
enforcement	1.0039	0.42384	2.3685	0.017876
pcms_2	-1.3101	0.44086	-2.9717	0.0029667
monramp	-11.346	0.45837	-24.752	2.2667e-132
vonramp	-2.2819	0.44286	-5.1525	2.6058e-07
activity	-3.7198	0.55649	-6.6843	2.4094e-11
pointmdl_2	-6.24	0.34239	-18.225	2.367e-73
pointmdl_3	-11.737	0.33769	-34.757	8.345e-254
pointmdl_4	-18.343	0.348	-52.71	0
pointmdl_5	-25.642	0.43224	-59.323	0
pointmdl_6	-30.642	0.67055	-45.696	0
pointmdl_7	-35.655	0.41662	-85.582	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.5. PCMS_3

Table E.5: MLRM outcome pcms_3

	Estimate	SE	tStat	pValue
(Intercept)	121.45	0.29098	417.38	0
flow	-0.00836	0.00026478	-31.573	2.6491e-211
truck	-19.772	0.7262	-27.226	4.9594e-159
enforcement	1.0013	0.42398	2.3616	0.018211
pcms_3	-1.1098	0.39984	-2.7757	0.005516
monramp	-11.345	0.45839	-24.75	2.3715e-132
vonramp	-2.3775	0.43362	-5.4829	4.2587e-08
activity	-3.7206	0.55652	-6.6856	2.3888e-11
pointmdl_2	-6.3133	0.33553	-18.816	5.3182e-78
pointmdl_3	-11.771	0.33694	-34.933	2.9864e-256
pointmdl_4	-18.331	0.35337	-51.876	0
pointmdl_5	-25.671	0.43136	-59.513	0
pointmdl_6	-30.67	0.67005	-45.773	0
pointmdl_7	-35.684	0.41574	-85.831	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.6. PCMS_4

Table E.6: MLRM outcome pcms_4

	Estimate	SE	tStat	pValue
(Intercept)	121.44	0.28999	418.78	0
flow	-0.0083604	0.00026476	-31.577	2.4016e-211
truck	-19.771	0.72616	-27.227	4.8822e-159
enforcement	0.99136	0.42404	2.3379	0.019407
pcms_4	-1.1267	0.37353	-3.0164	0.002563
monramp	-11.477	0.46036	-24.931	3.2134e-134
vonramp	-2.356	0.42736	-5.513	3.5917e-08
activity	-3.7176	0.55649	-6.6805	2.4727e-11
pointmdl_2	-6.3057	0.33133	-19.031	9.8969e-80
pointmdl_3	-11.745	0.33574	-34.982	6.3002e-257
pointmdl_4	-18.282	0.35538	-51.442	0
pointmdl_5	-25.541	0.43924	-58.148	0
pointmdl_6	-30.614	0.67154	-45.587	0
pointmdl_7	-35.678	0.41504	-85.963	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.7. PCMS_5

Table E.7: MLRM outcome pcms_5

	Estimate	SE	tStat	pValue
(Intercept)	121.42	0.2892	419.84	0
flow	-0.0083645	0.00026473	-31.597	1.3377e-211
truck	-19.77	0.72608	-27.228	4.7399e-159
enforcement	0.97511	0.42408	2.2994	0.021499
pcms_5	-1.2395	0.35588	-3.4829	0.00049763
monramp	-11.668	0.46742	-24.962	1.5192e-134
vonramp	-2.2805	0.42305	-5.3906	7.1364e-08
activity	-3.7252	0.55643	-6.6949	2.2425e-11
pointmdl_2	-6.262	0.32861	-19.056	6.2379e-80
pointmdl_3	-11.688	0.3347	-34.922	4.2334e-256
pointmdl_4	-18.204	0.35622	-51.104	0
pointmdl_5	-25.364	0.44959	-56.415	0
pointmdl_6	-30.463	0.67629	-45.045	0
pointmdl_7	-35.651	0.41474	-85.96	0

Number of observations: 13786, Error degrees of freedom: 13772 Root Mean Squared Error: 9.53
R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 2.79e+03, p-value = 0

E.1.8. No Enforcement

Table E.8: MLRM outcome without enforcement

	Estimate	SE	tStat	pValue
(Intercept)	121.46	0.28768	422.2	0
flow	-0.0083066	0.00026339	-31.538	7.5222e-211
truck	-19.842	0.72544	-27.352	1.8864e-160
pcms	-1.2977	0.33258	-3.9018	9.5935e-05
monramp	-11.872	0.48071	-24.696	8.5147e-132
vonramp	-2.3074	0.41673	-5.537	3.1337e-08
activity	-3.4982	0.56004	-6.2464	4.3234e-10
pointmdl_2	-6.2475	0.32524	-19.209	3.5915e-81
pointmdl_3	-11.669	0.3325	-35.095	1.6466e-258
pointmdl_4	-18.165	0.35655	-50.946	0
pointmdl_5	-25.217	0.46319	-54.441	0
pointmdl_6	-30.58	0.67109	-45.567	0
pointmdl_7	-35.658	0.41466	-85.993	0

Number of observations: 13786, Error degrees of freedom: 13773 Root Mean Squared Error: 9.53 R-squared: 0.725, Adjusted R-Squared 0.724 F-statistic vs. constant model: 3.02e+03, p-value = 0

E.1.9. Only WZ 2 and WZ 3

Table E.9: MLRM outcome WZ 2 and WZ 3

	Estimate	SE	tStat	pValue
(Intercept)	121.37	0.39422	307.87	0
flow	-0.0085286	0.00032215	-26.474	1.5159e-148
truck	-22.241	0.92475	-24.051	9.1443e-124
enforcement	1.5963	0.48809	3.2705	0.0010779
pcms	-0.81913	0.38823	-2.1099	0.034895
monramp	-11.15	0.58346	-19.111	9.0774e-80
vonramp	-1.8984	0.4822	-3.937	8.3144e-05
activity	-3.883	0.63872	-6.0794	1.2578e-09
pointmdl_2	-6.5813	0.43745	-15.045	1.6343e-50
pointmdl_3	-11.409	0.4575	-24.938	1.334e-132
pointmdl_4	-17.943	0.50157	-35.774	1.9144e-261
pointmdl_5	-25.346	0.58455	-43.36	0
pointmdl_6	-30.537	0.80173	-38.089	1.636e-293
pointmdl_7	-34.824	0.58721	-59.304	0

Number of observations: 8627, Error degrees of freedom: 8613 Root Mean Squared Error: 9.46 R-squared: 0.717, Adjusted R-Squared 0.716 F-statistic vs. constant model: 1.68e+03, p-value = 0

E.2. Belsley collinearity diagnostics

The condition indices(condIdx) of the Belsley collinearity test identify the number an strenght of any near dependencies between variables in the input of the multiple lineair regresion model[Goldstein, 2012]. The *collintest* of MATLAB decomposes the variance of the MLRM estimates in terms of the singular values(sValue) to identify variables involved in each near dependency, and the extent to which the dependencies weaken the regression.

A condition number of above 30, indicates multicollinearity in the model. As shown, this is not the case. The highest found condition index is that of activity which is not above 30. Activity has a high collinearity with flow (>0.5) and point (>0.5).

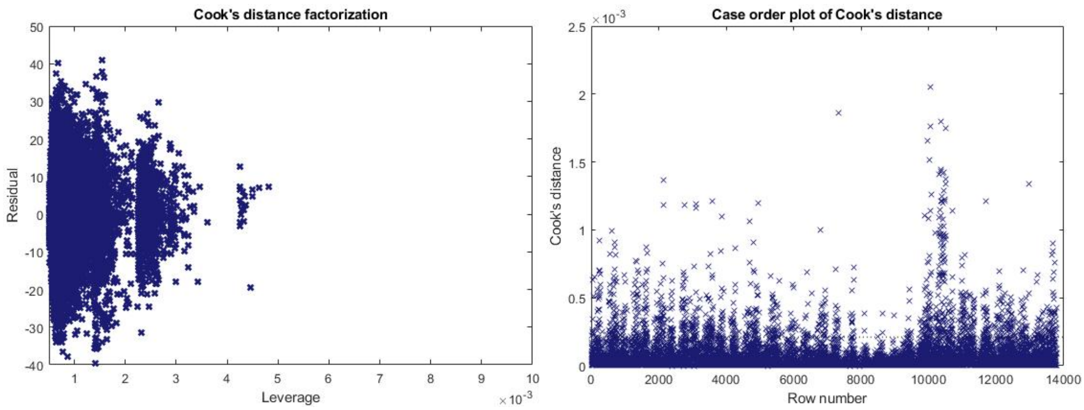
Table E.10: Belsley collinearity variance decomposition

	sValue	**condIdx**	**flow**	**point**	**truck**	**enforcement**	**pcms**	**monramp**	**vonramp**	**activity**
flow	1.7901	1	0.0209	0.0139	0.0211	0.0049	0.0129	0.0253	0.0063	0.0259
point	1.2122	1.4768	0.0020	0.0007	0.0103	0.0198	0.1448	0.0469	0.1935	0.0265
truck	0.9957	1.7979	0.0115	0.0005	0.0154	0.7970	0.0013	0.0102	0.0109	0.0316
enforcement	0.8187	2.1865	0.1124	0.0002	0.4421	0.0723	0.0258	0.0006	0.0228	0.0417
pcms	0.7846	2.2814	0.0036	0.0035	0.0018	0.0151	0.1314	0.3988	0.2683	0.1904
monramp	0.7294	2.4543	0.0818	0.0106	0.0009	0.0465	0.1038	0.0023	0.3453	0.5178
vonramp	0.6387	2.8026	0.1960	0.0081	0.0583	0.0442	0.4962	0.4577	0.0568	0.0112
activity	0.3302	5.4213	0.5719	0.9624	0.4501	0.0001	0.0838	0.0583	0.0963	0.1548

E.3. Model diagnostics

The model diagnostics show graphs of the cook's distance. The cook's distance describes the existence of outliers in the predictor values [Cook, 1977]. The dashed line in Figure E.1b shows the recommended distance of 3x the mean cook's distance. The points with a high cook's distance have a relatively large influence on the mean squared error regression.

It is shown a lot of variables have these large cook's distances, and this is an unfavourable situation. These large distances are related to the 'real problem', the heteroscedasticity of the model.



(a) Cook's distance factorization

(b) Case order plot of cook's distance

Figure E.1: Cook's distance model diagnostics