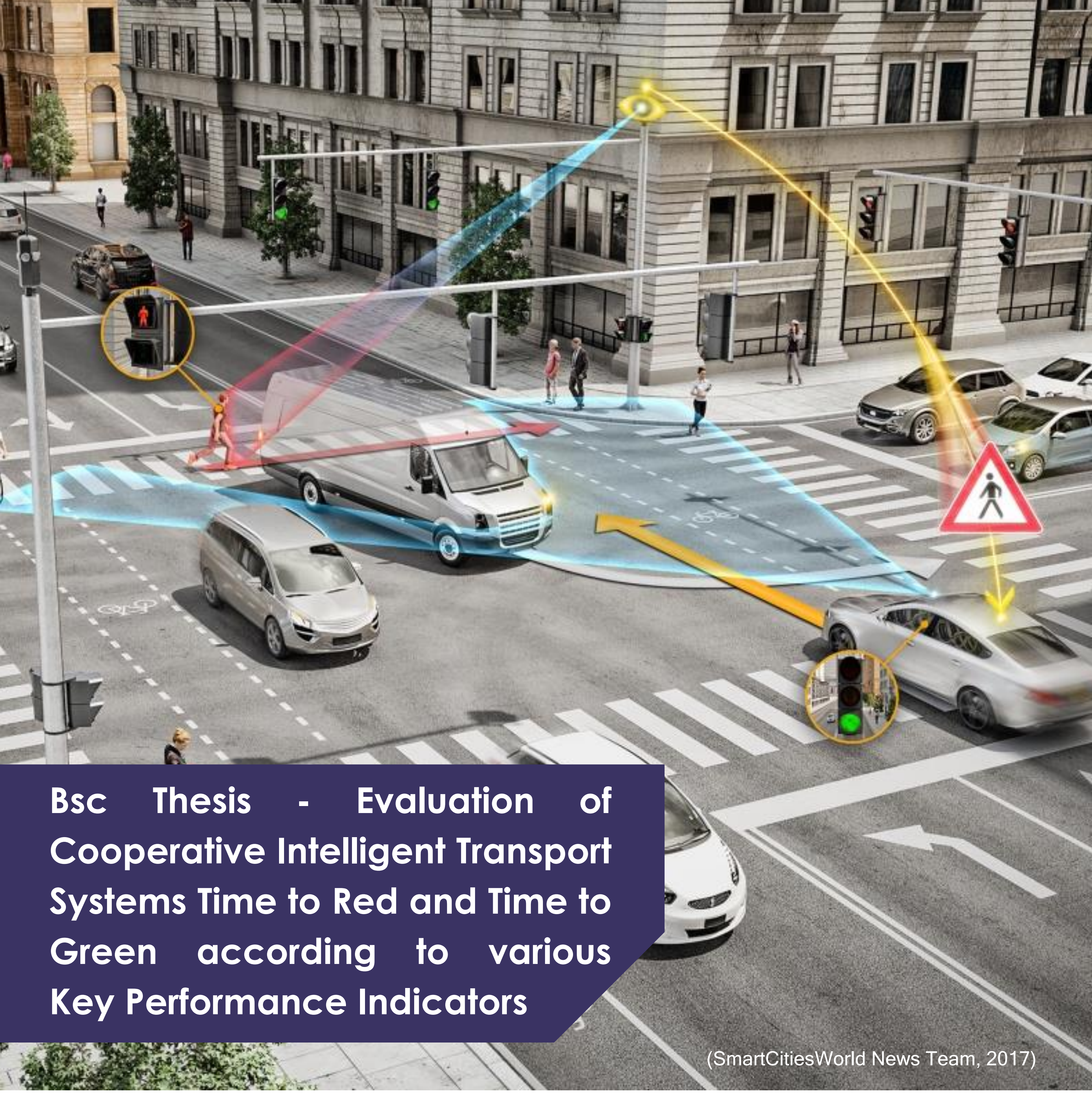

(SmartCitiesWorld News Team, 2017)

Bsc Thesis - Evaluation of Cooperative Intelligent Transport Systems Time to Red and Time to Green according to various Key Performance Indicators

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5 July 2022

Goudappel
MOBILITEIT BEWEEGT ONS

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PREFACE

Before you lies the final report of my Bachelor Thesis ‘Evaluation of Cooperative Intelligent Transport Systems Time to Red and Time to Green according to various Key Performance Indicators’. This thesis is the final part of my Bachelor’s programme in Civil Engineering at the University of Twente. This thesis is the result of a ten-week research that I carried out between April and July 2022 in cooperation with Goudappel. Within these ten weeks, I have learned a lot. For example, I have learned how it is to work on my own and got a glimpse of working within a consultancy firm in the working field of Civil Engineering.

I would like to thank my external supervisors at Goudappel, Leon Suijs, and Martijn Legêne, for guiding me through this process and for giving me a lot of advice. It was inspiring to get new insights based on the topics that came up during the discussions about the study. I would also like to thank my internal supervisor Oskar Eikenbroek for giving me feedback and useful insights and sometimes challenging my ambitious plans within my ten-week time frame. Finally, I would like to thank everyone at Goudappel who has helped me by answering my (many) questions, sharing their knowledge and information, and a nice time at the office.

Welmoed Spanjer

Enschede, 5 July 2022

ABSTRACT

English

This study assesses the effects when Cooperative Intelligent Transport Systems (hereafter: C-ITS) Time to Green and Time to Red are implemented. This assessment contains different aspects, namely environment, safety, efficiency, and driver comfort. When a driver uses Time to Green and Time to Red, he or she knows how many seconds a certain traffic light remains red or green. By researching these implementations, it can be determined whether this brings advantages or (more) dangerous situations. Real-life experiments with these applications have also been carried out, but these often took place in a small environment with a low penetration rate. During such a real-life experiment, many external factors can occur that cannot be taken into account. This makes it difficult to draw a proper conclusion about the findings. When the implementation takes place in a micro-simulation, this is not the case.

The research has been done in a microscopic program, PTV VISSIM. The implementation of the C-ITS applications was made possible by writing an external piece of code and linking it to this program. This code checks if the traffic light approaching vehicle is a C-ITS vehicle. If this is the case, the vehicle will be informed how long the traffic light will remain red (i.e. Time to Green) or how long it will remain green (i.e. Time to Red). With this information, appropriate measures can be taken. In the case of a Time to Red vehicle, different scenarios can arise. For example, when the traffic light will be green for a longer time. Because of this the C-ITS vehicles do not get a different speed and drive at their own desired speed on. It can also be that the traffic light is almost red. If it is doubtful whether the vehicle can drive through the green light, the speed will be increased to 60 km/h. This speed will be maintained for as long as necessary. This means that once it is certain that the vehicle can drive through the green light anyway, the speed will be reduced to the old desired speed. It may also be the case that the vehicle has to stop anyway because the travel time to the traffic light is too long and the time that the traffic light has a green light is too short. In this case, the required speed will be reduced to 20 km/h. This speed is chosen to simulate the throttle release. PTV VISSIM does not offer this itself. The latter situation may also occur in the case of Time to Green. In this case, the traffic light is on red longer than the travel time to the traffic light. The last scenario that can happen is that it is almost green. In this case, the desired speed is temporarily decreased to 20 km/h. As soon as the traffic light turns green again, the vehicle will return to the old desired speed.

The results of the model contain 11 different variants. The first variant is when no C-ITS is applied, the base measurement. In each subsequent variant, the number of C-ITS users increases by 10%. This process happens until there are 100% C-ITS users in the network. For the assessment of the model, four KPIs have been set up. These serve to check whether the implementation of Time to Red and Time to Green brings a benefit or not. These KPIs are environment, safety, efficiency, and driver comfort. Each KPI is linked to one or more outcomes of the model. For example, the environment has acceleration and deceleration, safety has the speed differences between sequential vehicles, efficiency has the average speed, stop delay, average queue length, and travel time, and finally, driver comfort has the number of stops of a vehicle.

The analysis of the results shows that the implementation of the C-ITS applications has different advantages and disadvantages. Positive effects can be seen regarding safety, environment, and a part of efficiency (average queue length). The negative speed differences between sequential vehicles decrease. For the environment, it can be seen that vehicles generally accelerate less and brake more slowly. The part of efficiency that shows positive results is the average queue length, which generally decreases considerably. Questionable results are also shown for driver comfort and part of efficiency

(stop delay). For driver comfort, it can be seen that the driver has to stop less often, which is a positive result. Only this does not apply to right-turning traffic. They do not have to use the traffic light and thus the C-ITS application, but they are (much) hindered by it. The same becomes clear from the results of the stop delay. Also here, the vehicles that turn right are hindered by the C-ITS application. Finally, there are also negative results for the last two efficiency outcomes, namely average speed and travel time. The average speed generally decreases, and the average travel time increases.

Dutch

Dit onderzoek beoordeelt de effecten wanneer *Cooperative Intelligent Transport Systems* (C-ITS) Tijd tot Groen en Tijd tot Rood worden geïmplementeerd. Deze beoordeling bevat verschillende aspecten, namelijk milieu, veiligheid, efficiëntie en comfort van de bestuurder. Wanneer een automobilist gebruik maakt van Tijd tot Groen en Tijd tot Rood, weet diegene hoeveel seconden een bepaald verkeerslicht nog rood of groen is. Door onderzoek te doen naar deze implementaties, kan worden gekeken of dit voordelen met zich meebrengt of juist (meer) gevaarlijke situaties. Er zijn ook al real-life experimenten met deze applicaties verricht, maar deze vonden vaak plaats in een kleine omgeving met een lage penetratiegraad. Tijdens zo'n real-life experiment kunnen er veel externe factoren optreden waar geen rekening mee gehouden kan worden. Hierdoor is het lastig een goede conclusie te trekken over de bevindingen. Wanneer de implementatie in een micro-simulatie plaatsvindt, is dit niet het geval.

Het onderzoek is verricht in een microscopisch programma, PTV VISSIM. De implementatie van de C-ITS applicaties is mogelijk gemaakt door er een extern stuk code te schrijven en te koppelen aan dit programma. Deze code gaat na of het verkeerslicht naderende voertuig een C-ITS voertuig is. Als dit het geval is, zal het voertuig te weten krijgen hoe lang het verkeerslicht nog rood is (dus Tijd tot Groen) of hoe lang het nog groen is (dus Tijd tot Rood). Met deze informatie kunnen bijpassende maatregelen genomen worden. In het geval van een Tijd tot Rood voertuig kunnen er verschillende scenario's ontstaan. Zo kan het verkeerslicht nog voor langere tijd op groen staan. Hierdoor krijgen de C-ITS voertuigen geen andere snelheid en rijden de voertuigen met hun eigen gewenste snelheid door. Het kan ook zijn dat het verkeerslicht bijna rood wordt. Als het twijfelachtig is of het voertuig door het groene licht kan rijden, zal de snelheid verhoogd worden naar 60 km/h. Deze snelheid zal worden aangehouden voor hoe lang nodig is. Dit houdt in dat zodra er zekerheid is dat het voertuig sowieso door het groene licht kan rijden, de snelheid weer verlaagd wordt naar de oude gewenste snelheid. Verder kan het ook zo zijn dat het voertuig sowieso moet stoppen omdat de reistijd naar het verkeerslicht te groot is en de tijd dat het verkeerslicht op groen staat te klein is. In dit geval zal de gewenste snelheid verlaagd worden naar 20 km/h. Er is voor deze snelheid gekozen om het gas los te simuleren. PTV VISSIM biedt dit namelijk niet zelf aan. Deze laatste situatie kan ook plaatsvinden in het geval van Tijd tot Groen. In dit geval staat het verkeerslicht langer dan de reistijd naar het verkeerslicht op rood. Het laatste scenario wat kan gebeuren is dat het bijna groen is. In dit geval wordt de gewenste snelheid tijdelijk verlaagd naar 20 km/h. Zodra het verkeerslicht weer op groen gaat, gaat het voertuig weer naar de oude gewenste snelheid.

De resultaten van het model bevat 11 verschillende varianten. De eerste variant is een nulmeting, hierin is geen C-ITS is toegepast. In elke volgende variant neemt het aantal C-ITS gebruikers met 10% toe. Dit proces gebeurt totdat er 100% C-ITS gebruikers in het netwerk zijn. Voor de beoordeling van het model zijn er vier KPI's opgesteld. Deze dienen om te kijken of de implementatie van Tijd tot Rood en Tijd tot Groen een voordeel brengt of niet. Deze KPI's zijn milieu, veiligheid, efficiëntie, en comfort van de bestuurder. Aan elke KPI is één of meerdere uitkomsten van het model gelinkt. Zo heeft milieu acceleratie en afremmen, veiligheid de snelheidsverschillen tussen opeenvolgende voertuigen, efficiëntie de gemiddelde snelheid, stop vertraging, gemiddelde wachtrij lengte en de reistijd, en als laatste comfort van de bestuurder heeft de aantal keren dat een voertuig moet stoppen.

De analyse van de resultaten laten zien dat de implementatie van de C-ITS applicaties verschillende voor- en nadelen heeft. Zo zijn er positieve effecten te zien op gebied van veiligheid, milieu en een deel van efficiëntie (gemiddelde wachtrij lengte). De negatieve snelheidsverschillen tussen opeenvolgende voertuigen neemt namelijk af. Op gebied van milieu is te zien dat voertuigen over het algemeen minder hard accelereren en langzamer afremmen. Het deel van efficiëntie die positieve resultaten weergeeft, is de gemiddelde wachtrij lengte. Deze neemt namelijk over het algemeen behoorlijk af. Ook zijn er twijfelachtige resultaten te zien voor de comfort van de bestuurder en een deel van de efficiëntie (stop vertraging). Voor de comfort van de bestuurder is te zien dat de bestuurder minder vaak hoeft te stoppen, wat een positief resultaat is. Alleen dit geldt dit niet voor het rechts afslaande verkeer. Zij hoeven geen gebruik te maken van het verkeerslicht en dus van de C-ITS applicatie, maar hebben hier wel (veel) hinder van. Ditzelfde wordt ook duidelijk uit de resultaten van de stop vertraging. Ook hier hebben de voertuigen die rechts afslaan hinder van de C-ITS applicatie. Als laatste zijn er ook nog negatieve resultaten te zien voor de laatste twee uitkomsten van efficiëntie, namelijk gemiddelde snelheid en de reistijd. De gemiddelde snelheid neemt over het algemeen af, en de gemiddelde reistijd toe.

TABLE OF CONTENT

1. INTRODUCTION

1.1 Problem Context

In recent years, the number of cars on the road has grown considerably (Eurostat, Statistics Explained, 2021). This growth in the number of cars pollutes the air with exhaust gases. This can have a negative effect on people's health. The implementation of Cooperative Intelligent Transport Systems (C-ITS applications) can contribute to finding solutions for the above problems. C-ITS applications enable communication between vehicle-vehicle (V2V), vehicle-infrastructure (V2I), and vehicle-environment (V2X). The only problem with this possible implementation, is that mainly (small) pilot studies have been done. Because of this, the penetration rate of these studies is often low and there are often external factors that come into play unintentionally. When research is done into these systems in a micro-simulation environment, this problem will not arise.

The aim of C-ITS applications is to improve the safety, comfort, and efficiency of transport (Mellegård & Reichenberg, 2020). When improving the efficiency of transport with the C-ITS application, the road capacity could be increased. These applications could also have other societal benefits. For example, the emissions of exhaust gasses can be decreased. There have been several studies on C-ITS applications, some with micro-simulation and others with real-life experiments. Some of these studies have also shown that C-ITS applications help to reduce the problems mentioned above. However, this is mainly seen from a technical point of view, as is done with simulation. How they should work in an operational world with all parties involved has not yet been investigated in detail. If this system were to be applied directly in reality, there would be little or no insight into the possible effects. If it were, it would improve traffic safety, efficiency, and sustainability in a more reliable and sustainable way.

Therefore, within this research, the effects and effectiveness of the implementation of C-ITS applications Time to Green and Time to Red are investigated under different scenarios in a controlled environment (micro-simulation). Hereby, possible behavioural changes of people are taken into account. These behavioural changes were applied to vehicle speed and reaction time.

1.2 Study area

This research is part of a project that Goudappel carries out on behalf of the Research Institute of Sweden (RISE). The outcome of Goudappel’s project will serve as a guideline for the investigation of cost and benefit analyses regarding C-ITS traffic signals for cities. The full research of Goudappel takes place at several intersections in Sweden in the municipalities of Gothenburg, Stockholm, and Uppsala (Goudappel & Rise, 2022). The intersection under investigation is located in Uppsala and is a signalised intersection with a static regulation. Furthermore, cars and busses are present at this intersection.

Although this research will only be focussed on one intersection, a big network of Uppsala will be used. The roads of this network are displayed in Figure 1. In this figure, the location of the investigated intersection is highlighted with a red box. The traffic light system in Sweden is slightly different from that in the Netherlands. The light cycle in Sweden is green, amber, red, red/amber, green, etc. Whereas in the Netherlands it is green, amber, red, green, etc. Due to Sweden's red/amber, drivers know that it is almost green before it is actually green.

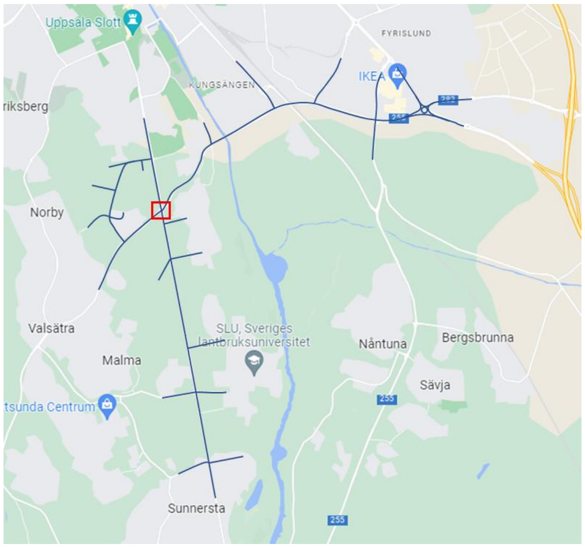

Figure 1: Investigated study area of Uppsala, Sweden (Google, 2022)

1.3 Research Objective

The implementation of C-ITS can be quite an investment. Therefore, it is important to know if the investments will have (social) benefits, such as comfort for the driver, improved road capacity, or positive influence on the environment if C-ITS would be implemented. There have been (small) pilots, but due to the low penetration rate and the small areas investigated, it is difficult to estimate the real effects of the C-ITS implementation (Goudappel & Rise, 2022). Moreover, it is also difficult to estimate what exactly will change due to the C-ITS implementation, as many factors can change (e.g. weather or traffic). This problem does not arise when a simulation environment is used. By carrying out a micro-simulation, it is possible to assess the effects in practice before they are actually implemented. Within this micro-simulation, the behavioural aspect is also relevant. It is unknown how people react to such an implementation. This makes it possible to investigate whether these investments are worthwhile to implement and whether there is a real need for them in the area.

Therefore, with this analysis, a micro-simulation is done which investigates the effects and effectiveness of the implementation of C-ITS applications Time to Green and Time to Red. This analysis also includes changes in human behaviour which are expected with this implementation.

There are certain aspects that are left out in this analyses, due to the (small) time frame of this bachelor thesis. Therefore, it has been chosen to narrow the following three things down, which are described below.

- The first point is the C-ITS application. There is only looked into the C-ITS application Time to Green and Time to Red.
- Secondly, in one of the sub-questions, Key Performance Indicators (hereafter: KPIs) is mentioned. Within this sub-question, an assessment framework will be made based on different KPIs. These KPIs are based on the possible output of PTV VISSIM, such as efficiency, (social) benefits for people, and traffic indicators.
- Third and last, only one intersection of the large network is considered.

With the previous items in mind, the objective of this study will be:
"To evaluate the effects of C-ITS Time to Green and Time to Red on efficiency, comfort of driver, safety and sustainability at a signalised intersection in a simulation environment."

1.4 Research Questions

The research objective focuses on the effects of the implementation of C-ITS applications. To get to the effects of these applications, it is needed to have a model to obtain a quantitative result. There are no models yet which describe this situation. The main question of this research is, therefore:
"What are the effects of C-ITS applications Time to Green and Time to Red on efficiency, comfort of driver, safety, and sustainability at a signalised intersection in a simulation environment?"

Efficiency, comfort of driver, safety, and sustainability are really broad terms. Therefore, several outcomes of the simulation results can be linked to these terms. The length of queue, delay time, average speed, and travel time are part of efficiency. The number of stops is covered by the comfort of driver. Speed differences are part of safety. Sustainability will cover acceleration and deceleration.

The main question is subdivided into five sub-questions. The first sub-question focuses on the C-ITS applications in general.

1. Which C-ITS applications exist, what are their functions, and what is the added value of the different systems regarding efficiency, comfort of driver, safety, and sustainability?

The second sub-question focuses on the characteristics of human behaviour. This is necessary so that it is clear what possible input values can be and what can be adjusted in PTV VISSIM. As it is a simulation study, many behavioural characteristics will not be used.

2. What are behavioural characteristics of people that could have an effect on C-ITS applications?

In order to see whether the model can actually answer the main question, it is important to draw up an assessment framework. This will be answered in the third sub-question.

3. Which KPIs and behavioural characteristics (of sub-question 2) can be translated into criteria, such that an assessment framework can be drawn up?

A big part of this research is about the C-ITS applications Time to Green and Time to Red. Therefore, the fourth sub-question is about the implementation of these applications.

4. How can a realistic Time to Green or Time to Red system be implemented in PTV VISSIM?

At the end, all the results are in. The final step is to connect everything together. This will be done in the fifth sub-question. In this question, the assessment framework will be filled in with the results.

5. What are the effects in terms of sustainability, efficiency, driver comfort, and safety when looking at network-wide and individual results?

2. LITERATURE RESEARCH

Numerous studies have been done regarding C-ITS applications. In this chapter, the main findings in the context of Time to Green and Time to Red are presented. The information which is provided here is later in the methodology partly used.

As mentioned in the previous chapter, this research will mainly focus on C-ITS applications Time to Green and Time to Red. However, the function of GLOSA and prioritisation are also discussed, as they are also part of Goudappel's project. The studies about these C-ITS applications could contain some information that is applicable for the Time to Green and Time to Red applications. Therefore, the GLOSA and prioritising applications will serve as support for the Time to Green and Time to Red applications.

2.1 Cooperative Intelligent Transport Systems (C-ITS)

Cooperative Intelligent Transport Systems (C-ITS) applications make communication between vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-environment (V2X) possible. By implementing these applications in traffic, safety, comfort and efficiency of traffic can be improved (Mellegård & Reichenberg, 2020).

Since C-ITS applications can be of added value to traffic systems, it has been the subject of many studies. There are several types of applications that are currently being researched. These types are described below.

2.1.1 Time to Green & Time to Red

Time to Green and Time to Red are part of Traffic Signal Countdown Timers (TSCT). This technology informs road users how long a traffic light remains red or green. With this technique, road users receive real-time information, which can help to increase road capacity. This technique helps drivers to decrease the start-up lost time. When this time is decreased, more vehicles can go through the green cycle.

The research by Limanond et al. (2009) showed that during daytime hours timers do not have much effect. During these periods, the saturation threshold has already been reached without the countdown timers. This could be due to the time pressure drivers feel and therefore leave less room on their predecessor when entering the intersection. This leads to the smallest possible saturation threshold, regardless of whether a countdown timer is used or not.

2.1.1.1 Headway

The headway is the time or distance between vehicles following each other when passing a certain point on a lane. This point is measured from the same point of each vehicle. This could, for example, be the stop line at a traffic light, which indicates that you must wait for the light before that line. According to the research of Limanond et al. (2009), the first vehicle in a standing queue at a traffic light has the longest time headway relative to the start of the green cycle. This can also be seen in Figure 2. This is often the longest driving time since the driver has to notice and anticipate towards the change of traffic light colour. After the first vehicle, the headway decreases. The decrease of the headway happens up and until the fifth vehicle. After the fifth vehicle, the headway stays quite constant. The fifth and other following vehicles have fully anticipated to the change of the traffic light and have followed the car in front with the same (increasing) speed. Although this is based on a model perspective, it still gives a good indication of the mean headway of vehicles. In reality, it is a lot more difficult, since the reaction time could vary a lot per driver, for example.

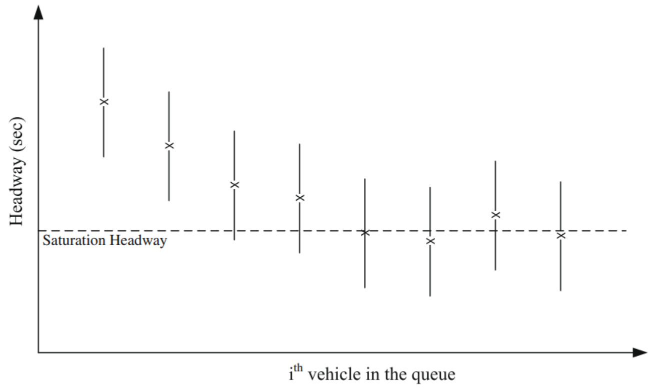

Figure 2: Conceptual headway pattern of vehicles in a standing queue (Limanond, Chookerd, & Roubtonglang, 2009)

2.1.1.2 Countdown traffic lights

In the same research Limanond et al. (2009) conducted an experiment on a rigid signalised intersection in Bangkok. They found that when TSCT installations are installed, the efficiency of the intersection can be improved, which can also be seen in Figure 3. In this figure, the different mean headways with and without timer during different times of the day are displayed. During this experiment, the countdown timer displayed the time remaining until the next green phase. Although the saturation headway did not decrease, the start-up lost time could be reduced by 1.00-1.92 seconds per cycle. This is on average 0.5-1 extra vehicles per cycle. This equates to an extra 8-24 vehicles per hour per lane. The reaction time of the driver, which is normally 1.00-1.50 seconds, is thus decreased.

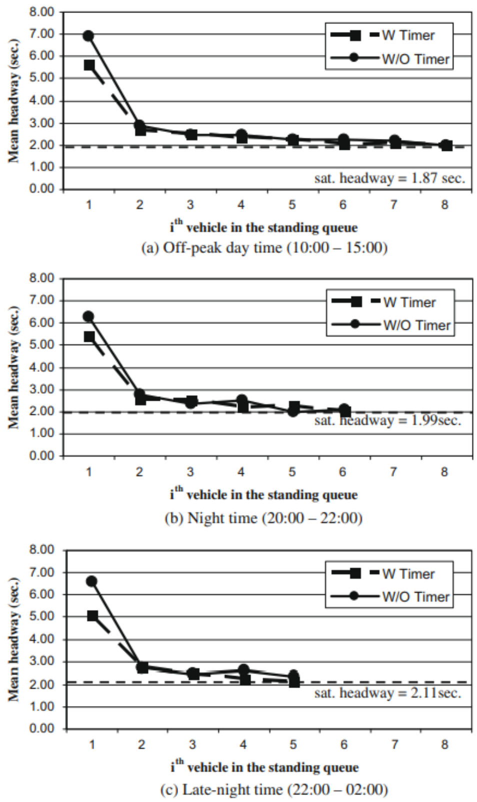

Figure 3: Comparison of headway patterns of the first few vehicles in the standing queue with and without presence of a countdown timer at different moments of a day (Limanond, Chookerd, & Roubtonglang, 2009)

A similar experiment with such a countdown traffic light for vehicles was also done in 's Hertogenbosch, the Netherlands. This traffic light had a countdown integrated in the amber part of the traffic light which counted down in 3-2-1 or 2-1 seconds. To implement this system, two boundary conditions were set up:

1. The green light cannot be delayed or skipped;
2. The waiting traffic on the lanes in front of the traffic light should be at least be 2 seconds detected by a detection loop. This prevents that vehicles still have some speed (they could have a "flying start") which could endanger the safety. Because of this, all traffic always starts from a standstill. If vehicles are not detected by the detection loop for at least 2 seconds, the countdown is not shown.

In Figure 4 and Figure 5 two graphs are visible. These graphs display the differences between the 3 seconds timer, 2 seconds timer, and no timer. As can be seen, the results with timer have a positive effect on traffic efficiency. Figure 5 for example, clearly shows that vehicles accelerate faster when using the countdown traffic light.

The 3 seconds timer has a more positive influence on the travel time. The departure time (when standing still) with a 3 seconds timer was just above one second faster compared with the without timer situation. The departure time (when standing still) with a 2 seconds timer was around 0.8 seconds faster compared with the without timer situation.

At the beginning of the pilot period of this research, the countdown timer was set to 3 seconds. However, due to quite a big number of early-starters in this scenario (10%), some unsafe situations could happen. Therefore, the timer was set to 2 seconds. This increased the departure time a bit (compared with the 3 seconds timer), but this had a positive effect on the early-starters, since this number decreased to just above 4% (van der Burgt & Greweldinger, 2018).

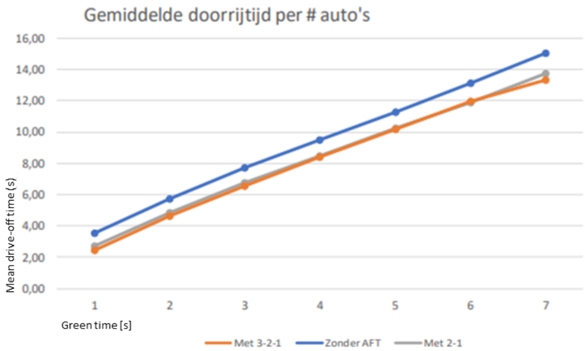

Figure 4: Green time versus mean drive-off time (van der Burgt & Greweldinger, 2018)

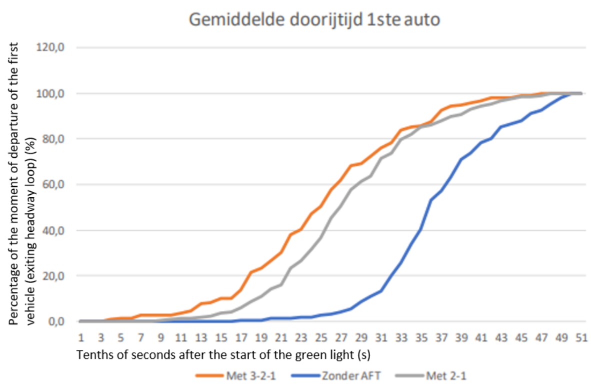

Figure 5: Tenths of seconds after the start of the green light versus percentage of the moment of departure of the first vehicle (van der Burgt & Greweldinger, 2018)

2.1.1.3 Environment
Research by Sokolov et al. (2018) shows that when drivers are provided with traffic signal information, the drivers that make use of this have a smoother driving pattern. Furthermore, extreme acceleration and deceleration arise less frequently within the group that uses the system. In that group, there is a reduction of 7,6% seen. The study by Bokare and Maurya (2013) describes the influence of accelerations and emissions. This study makes it clear that when the gears are less hard, fewer emissions are produced.

2.1.1.4 Safety
There have been quite a few studies on the safety aspect of countdown traffic lights. By using the traffic lights incorrectly, it can cause dangerous situations in traffic. For example, the research of Chen (2007) investigated the safety results of several intersections with Time to Green. In some cases the number of reported crashes doubles, and the number of injuries increases with 33%. The study of Krukowicz et al. (2021) shows that the countdown traffic light causes more vehicles passed the traffic light while the traffic light was amber or red. This can endanger the safety of the other road users. Furthermore, studies by Yuan et al. (2009) and Zhang et al. (2012) state that traffic speeds up in the last few seconds of the green and amber period of the traffic light.

There are also studies that contradict this and say that the traffic situation becomes safer as a result. The results from Time to Red, on the other hand, show something else and look more promising. At intersections with Time to Red, a reduction of 50% in total crashes and number of injuries was seen (Chen, 2007).

2.1.1.5 Summery Time to Green and Time to Red
In conclusion, with the C-ITS application Time to Red and Time to Green, the driver gets to know how long a traffic light remains red or green. This implementation can have several advantages and disadvantages. For example, research by Limanond et al. (2009) and van der Burgt and Greweldinger (2018) shows that vehicles drive away faster when the C-ITS application is used. Furthermore, research by Sokolov et al. (2018) shows that there are fewer extreme accelerations and decelerations. Finally, there are several studies that show that traffic safety deteriorates when the system is used. However, Chen's (2007) research shows that there is a 50% decrease in the total number of crashes and the number of injuries when only Time to Red is introduced.

2.1.2 GLOSA
Green Light Optimised Speed Advisory (GLOSA) is another type of a C-ITS application, which aims to improve efficiency and safety of traffic (Mellegård & Reichenberg, 2020). This system uses a connection between the vehicle and traffic lights. With this connection, an advisory speed can be given to the driver. This way the driver can, when necessary, adjust his or her speed. In this way, there will be less excessive braking and accelerating, which is a good effect for the environment since there would be less emissions.

In section 2.1.2.1 and 2.1.2.2 information about certain scenarios and the effects of GLOSA are described. In the research of Stevanovic et al. (2013), different scenarios are described: with or without GLOSA, fixed-time or actuated control, and a variation of different activation frequency of GLOSA. Fixed-time control means that every cycle has the same length, and the green and red time are constant. With actuated control, the system detects arriving traffic and assigns the appropriate light cycle. For this research, PTV VISSIM was used to simulate the traffic.

2.1.2.1 Efficiency

The above described results of the simulations, can be seen in Figure 6 and Figure 7. In these figures the delay of the stopped vehicles is shown. For the scenarios without GLOSA, the mean is taken. In both comparisons it can be seen that the scenarios with GLOSA have a positive influence on the delay of the vehicles. With these figures it can also be seen that the fixed-time control is way more efficient than the vehicle actuated control. This is due to the fact that GLOSA redistributes the vehicle delay from delay of stationary intersections to the delay of moving vehicles. This delay is caused by the speed reduction which is given through the speeds advisory message (Stevanovic, Stevanovic, & Kergaye, 2013). A remarkable point of Figure 7, is the fact that the optimum of the actuated control is around 40% users.

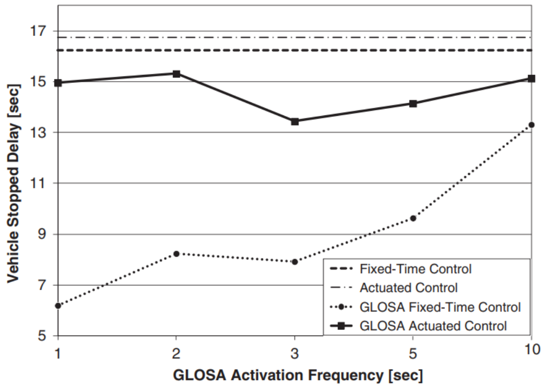

Figure 6: GLOSA Activation Frequency versus Vehicle Stopped Delay (Stevanovic, Stevanovic, & Kergaye, 2013)

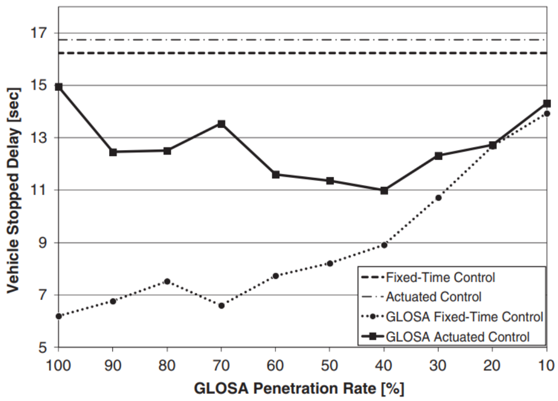

Figure 7: GLOSA Penetration Rate versus Vehicle Stopped Delay (Stevanovic, Stevanovic, & Kergaye, 2013)

The simulated studies of Gajananan et al. (2013) and Olaverri-Monreal et al. (2018) found that the use of GLOSA made the drivers drive more smoothly. When GLOSA was used, the total travel time, number of stops, waiting and starting-up times decreased, and an increase of average speed was found. The simulation study of Preuk et al. (2016) found the drivers approached the traffic light without unnecessary speed variations. Furthermore, a research of Suzuki, H. and Marumo, Y. (2020) shows that the implementation of GLOSA safer traffic flows in a simulated environment achieve.

2.1.2.2 Fuel consumption

When comparing the fuel consumption of vehicles with the different scenarios, some differences are noticed. For the scenarios without GLOSA, the mean is taken. As there can be seen in Figure 8 and Figure 9, GLOSA has not automatically a positive influence on the fuel consumption of the vehicles. The test with GLOSA actuated control does not or rather late (penetration rate of 40%) have a positive influence on the fuel consumption. This is not the case for the test with GLOSA fixed-time control. This can have a positive influence of the fuel consumption, as long as the activation frequency would be 3 seconds or less and/or the penetration rate 30% or higher. Frequent updates to the driver enable the system to better estimate a recommended speed. As a result, the vehicle will be able to maintain a more constant speed, which in general will reduce the number of accelerations or decelerations.

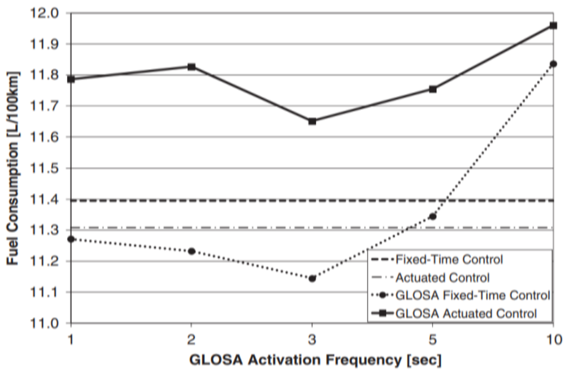

Figure 8: GLOSA Activation Frequency versus Fuel Consumption (Stevanovic, Stevanovic, & Kergaye, 2013)

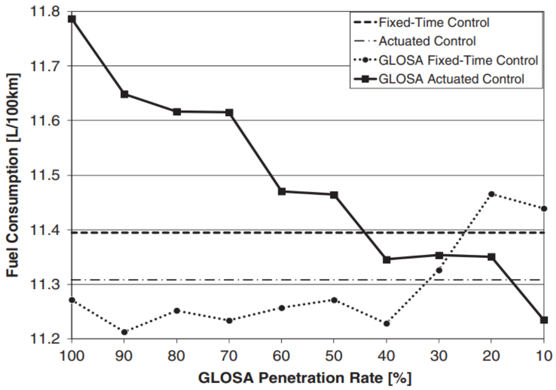

Figure 9: GLOSA Penetration Rate versus Fuel Consumption (Stevanovic, Stevanovic, & Kergaye, 2013)

2.1.2.3 Summery GLOSA

With regard to GLOSA, a number of studies have been carried out in terms of efficiency and fuel consumption. These results show that when GLOSA is applied in traffic, efficiency goes up. This depends on the situation, such as activation frequency, penetration rate, fixed-time control or actuated control. With regard to safety, no research has been found that shows a decrease.

2.1.3 Prioritising

There are already certain methods that give priority to different traffic types that are C-ITS applications. These give priority to, for example, busses who are running behind on their travel times.

2.1.3.1 Public transport

Public transport priority can be passive or active. When passive traffic signal priority is implemented, the cycle time to the traffic signal is fixed. In this situation the green time will be extra-long. This longer green time is always applied, even though there is no bus at that moment at the traffic signal. With active traffic signal priority, the cycles of the traffic lights can adjust to different needs of the intersection. This means that when, for example, a bus is detected, the green cycle for that way can be extended, shorten the red cycle, or an extra (short) green cycle can be implemented. In general, the travel time of the prioritised transport will decrease. However, the travel time for other vehicles will increase.

With traffic signal priority for public transport, it is possible that the cycles of the traffic lights adjust to different needs of the intersection. This means that when, for example, a bus is detected, the green cycle for that way can be extended, shorten the red cycle, or an extra (short) green cycle can be implemented. In general, the travel time of the prioritised transport will decrease. However, the travel time for other vehicles will increase (Wahlstedt, 2014).

2.1.3.2 Summery Prioritising

Prioritising means giving priority to a certain target group in traffic. This can be, for example, a bus line that cannot reach the next stop in time because of traffic congestion on the road. When prioritising is applied, the travelling time, emissions and number of stops for this group is reduced. This is not the case for the other traffic participants.

2.2 Human behaviour in traffic

This section of the chapter explains how behaviour can affect traffic. In the first part, the focus will be on the acceleration behaviour of the driver and an example is given. The second part will focus on the behavioural implementation in relation to the C-ITS applications is discussed in more detail.

2.2.1 Acceleration behaviour

When a driver approaches a traffic light, this person has basically three options: accelerate, brake, or do nothing. Figure 10 shows an example of how the speed of a vehicle waiting at a traffic light can fluctuate. This figure shows how a vehicle starts moving from standstill. The vehicle arrives at a red traffic light, where it comes to a complete stop. At t = 40, the traffic light changes to green. The vehicle accelerates again and approaches a second traffic light. This light is initially red, but at t = 60, it changes to green. After this, the vehicle accelerates some more and comes to a stop at t = 85.

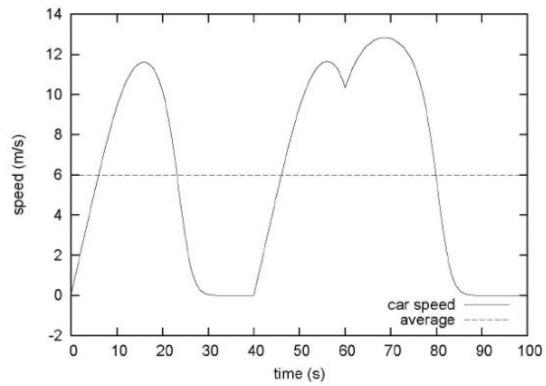

Figure 10: Acceleration of a vehicle (Sánchez, Cano, & Kim, 2006)

There are four models that describe the acceleration behaviour of vehicles when the initial speed is zero. These are shown in Figure 11 shown. This hard or soft acceleration behaviour depends on several factors, such as comfort, traffic density, type of vehicle, environment, and fellow road users (Wang, Dixon, Li, & Ogle, 2004).

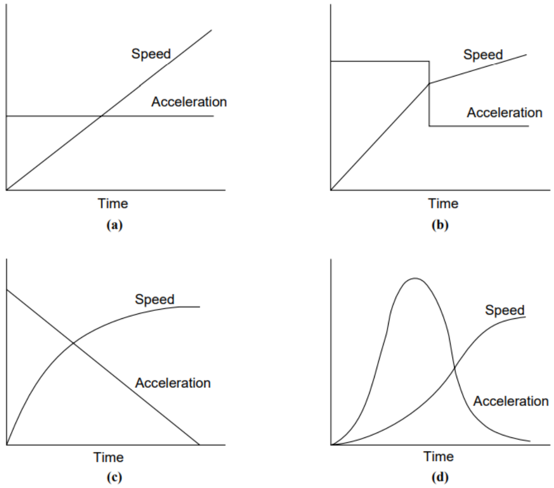

Figure 11: Four common acceleration models: (a) constant, (b) two-phase, (c) linear decreasing, and (d) polynomial (Wang, Dixon, Li, & Ogle, 2004)

What emerges from each model is the fact that vehicles accelerate at the beginning is hard. This causes the speed to increase. The further the driver gets towards the desired speed, the less acceleration occurs.

2.2.2 Behaviour in combination with C-ITS applications

Several studies have been conducted regarding the behaviour in combination with different C-ITS applications. One of these studies focuses on the feeling that drivers get from the system when they use it. Rittger et al. (2015) found that drivers had the feeling that they were annoying other drivers more often than they actually were. This feeling can make drivers feel awkward and therefore not adhere to the recommendations of the system.

In a study by Preuk et al. (2016), it becomes clear that the non-GLOSA users will follow the driving behaviour of the GLOSA users. This was perceived as pleasant according to these users. This contradicts with the research of Rittger et al. (2015) as that simulation study revealed that the non GLOSA users can get angry. This can lead to dangerous situations, such as overtaking these GLOSA vehicles when there is not enough room to do so.

2.2.2.1 Summery human behaviour in traffic

In terms of human behaviour in traffic, it can be seen that drivers accelerate faster at the beginning than when they have almost reached their desired speed. Furthermore, several studies have been done on the combination of C-ITS applications and human behaviour. Here it appeared that C-ITS users can feel uncomfortable when using them. Because they experience this, they may start to ignore the recommendations. Furthermore, the studies showed that the vehicles that do not use the system, can be irritated by the C-ITS users. This can lead to dangerous situations.

3. RESEARCH METHOD

This chapter will explain the research methodology. The different steps made were performed and how this was done will be explained.

As previously mentioned, this thesis will investigate the implementation of Time to Green and Time to Red with regard to different objectives using a range of KPIs. In order to investigate this, PTV VISSIM will be used. With PTV VISSIM it is possible to reconstruct more or less the reality. The advantage of the modelling programme is that it is a closed environment, which means that no uncontrollable external factors can play a role. This makes it possible to identify when an implementation is working or not, considering different conditions. Furthermore, PTV VISSIM has the advantage that there are a lot of possibilities. It is also possible to adjust the capacity of different intersections, number of vehicles entering the network, or behaviour of drivers, and pedestrians.

As this research is done in PTV VISSIM, the method used may differ from how it would look in real life. In real life, each individual C-ITS driver would be given a time that would tell them how long a traffic light remains red or green. This chapter will also describe how the micro-simulation implementation can deviate from reality.

3.1 Creating assessment framework

The first part of this research concerns the drawing up of an assessment framework. With this assessment framework, the possible effects of the implementation of the C-ITS application in the simulation environment can be determined. When this assessment framework is made before the implementation in the model of Time to Green and Time to Red, the focus of this implementation will be more on the KPIs. This makes the implementations more targeted and they can be compared in different situations. This makes it also applicable for the assessment of other types of C-ITS applications, such as GLOSA. This framework will be based on the literature study and KPIs. The KPIs that will be used in this study are described below. The order of describing the KPIs is completely arbitrary.

3.1.1 Environment

The first KPI is about the environment. The influence of the C-ITS applications on the environment will be based on the results of the acceleration and deceleration (Bokare & Maurya, 2013). When drivers let the vehicle roll out instead of (fast) braking, there is a possibility that they will not have to come to a complete stop. If this is the case, it saves fuel as they have to accelerate less to get back up to their desired speed. This means that when the results of accelerating decrease and the ones of decelerating increase, it has a positive effect on the environment since there will be fewer emissions.

3.1.2 Safety

The second KPI will focus on the safety of the drivers. During normal traffic situations, a vehicle will (generally) follow its predecessor in terms of speed, unless this is very much higher or lower than the driver's desired speed. When drivers know how long a traffic light remains red, amber, or green, they can adapt their speed. This may cause a driver to be more aggressive or passive, for example. This can lead to dangerous situations if other drivers do not know what these times are. In order to take this into account within the study, the observed average speed differences between the sequential vehicles will be examined.

Another point that addresses safety, is the unexpected part when a car suddenly drives slower than usual. This could happen when the traffic light is green but the driver knows the light will be red when he/she arrives at the traffic light. The vehicle which is following the decelerating car would not expect it and an accident could happen. The same situation could also happen the other way around. A vehicle could already start accelerating even though the traffic light is still red. In this case, the accelerating vehicle starts to follow the next car and can adjust the speed, if necessary, to that vehicle. However, this part of the safety risk is not included in this study.

3.1.3 Efficiency

The third KPI is about the efficiency of the C-ITS applications. This KPI has three outputs that can be linked to it, namely the length of the queue, stop delay, and average speed. Based on the results of these outcomes, it will be examined whether this increases or decreases when Time to Red and Time to Green are applied, and whether this has a positive or negative effect.

3.1.4 Comfort of the driver

The fourth and final KPI focuses on driver comfort. Only one output can be linked to this KPI, namely the number of stops. For this KPI an educated guess is made that if the number of stops decreases when Time to Green and Time to Red are introduced, this will have a positive effect. The KPI will have a negative effect when the number of stops increases.

3.2 Assumptions

In order to create a realistic simulation environment, it is necessary to make a number of assumptions. These assumptions were made before the model was created and executed. The assumptions are explained in this section. Furthermore, there are a few assumptions that explain how this implementation in the micro-simulation environment can differ from a real-life implementation.

The first assumption that will be made concerns the behavioural part of the model. It is assumed that the model which is used, the reality imitates. In this model, a piece of behavioural changes is applied, which is also assumed to be realistic. With this in mind, a good impression of the effects, in reality, can be obtained from the results of the simulations. More about the behavioural aspect within the implementation are presented in section 3.6.

The second assumption concerns the traffic light cycles. In the original model, the traffic signals under investigation is vehicle activated. Based on viewing the intersection during a number of simulations and the traffic volume from the different directions, an estimation was made for a rigid traffic light regulation. More information about the traffic light regulation can be found in section 3.4.

The third assumption is about the reaction distance. At 200 metres from the traffic light, C-ITS drivers will receive a notification from the application. If the desired speed of the vehicles is by default around 50 km/h, this means that they have around 14.4 seconds to react until they reach the traffic light. While covering this distance, there are four possibilities that the driver can do, accelerate, brake (release the throttle), maintain current speed, or a combination of the previous points. When the car is within that particular range, a continuous check is done to know exactly what the possibilities are for that particular vehicle.

The fourth assumption concerns the reaction to the system. These C-ITS drivers immediately obey the message they receive from the system and will not abuse or ignore it.

The fifth and final assumption is more based on the model. As already mentioned at the beginning of this section, the implementation of Time to Green and Time to Red in this micro-simulation environment is quite different from the possible real-life implementation. In the simulation environment, the assumption is made to use two traffic lights. One of them is green 1 second earlier each time. This is set up so that only C-ITS vehicles can use it. The other traffic light is with the 'normal' green times. This method was chosen to give the C-ITS vehicles the information earlier and thus manipulate the response time. The reaction time of the C-ITS users in the model is 1 second faster than the non-users. More information is given in section 3.6.1 Reaction time of driver.

3.3 Information regarding the investigated intersection

Figure 12 shows an overview of the investigated intersection. It also shows the numbers 1 to 7. The numbers represent the corresponding signal groups. More information about this will follow later in section 3.4.

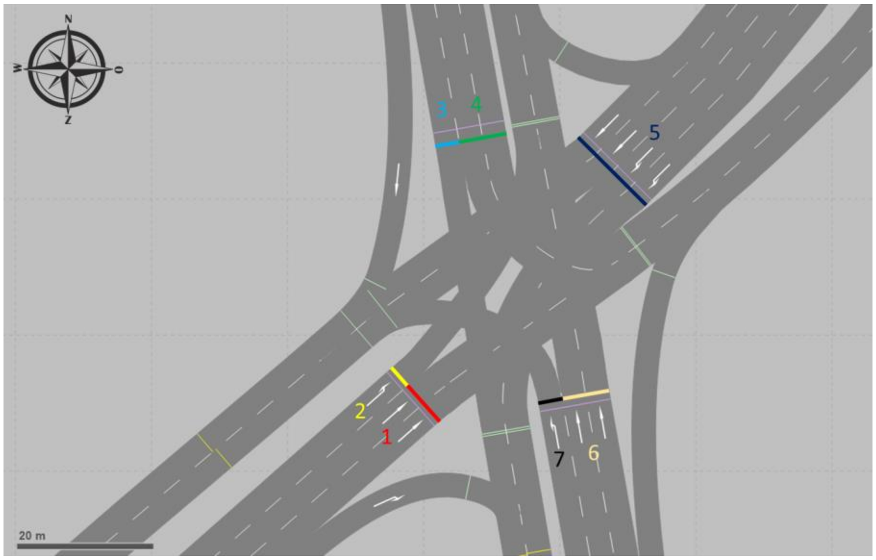

Figure 12: Overview of the investigated signalised intersection

The simulations are done with vehicle input during rush hour. There are in total 12 routes that the vehicles can take. The tables below show the data. Table 1 shows the percentages of the vehicles that take a particular route, Table 2 shows the same but then in the actual amount of vehicles. On the side of Table 2, the total sum of that particular direction is also shown.

Table 1: Overview of vehicle input in turning percentages

	West	North	East	South
West	-	14,0%	80,7%	5.3%
North	11,6%	-	42,9%	45,5%
East	49,4%	11,2%	-	39,4%
South	6,1%	25,5%	68,4%	-

Table 2: Overview of vehicle input in actual amount of vehicles

	West	North	East	South	Total
West	-	106	610	40	756
North	101	-	374	396	871
East	813	185	-	649	1647
South	65	273	731	-	1069

3.4 Traffic light regulation

As already mentioned in section 3.2, the different assumptions of this study are described. One of those assumptions is about the traffic light regulation. In this section, more information about this regulation is given.

In reality, there will only be one traffic light in each direction. In this simulation environment, there will be two traffic lights, one working for all Time to Red and Time to Green vehicles, and one working for the other traffic (i.e. non C-ITS vehicles, buses, and trucks). Both traffic lights are red at the same time, but the C-ITS traffic light becomes green one second earlier per direction. This simulates that the C-ITS vehicles have more knowledge in advance and therefore can anticipate earlier. The green and red times differ per direction. Therefore, Figure 13 and Figure 14 show the green and red times per signal group, and Figure 12 the signal groups per direction.

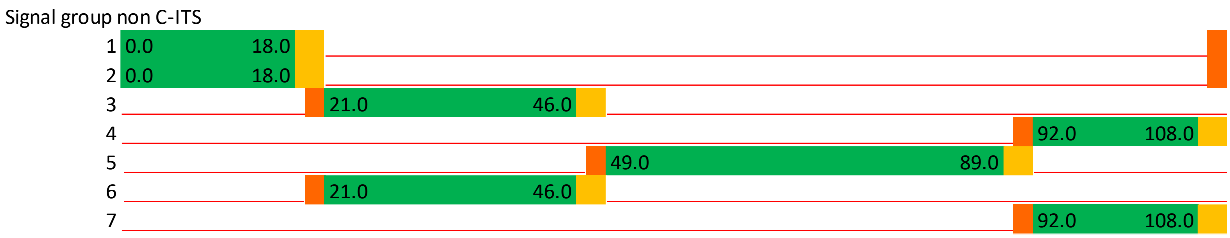

Figure 13: Rigid traffic light regulation of signal groups of the non-C-ITS vehicles

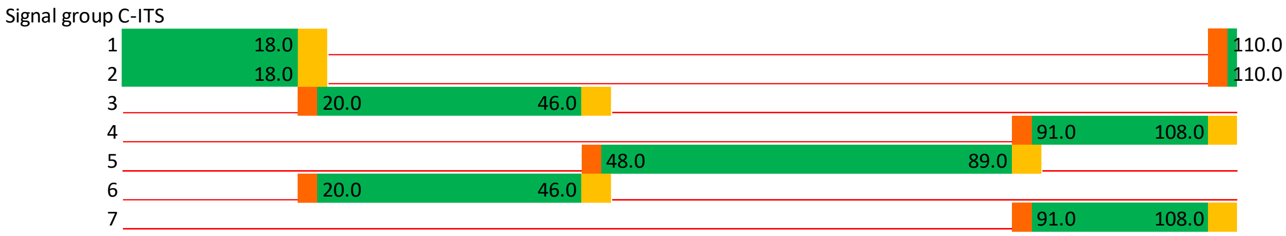

Figure 14: Rigid traffic light regulation of signal groups of the C-ITS vehicles

In Figure 13 and Figure 14 the green and red times of the different signal groups are displayed. The whole cycle to the traffic light is 111,0 seconds. The numbers which are displayed in the green part of the figures are the times when the traffic light is green. These times differ per direction. The brighter orange is the time the traffic light is amber and is always 3 seconds. The darker orange represents the time when both red and amber lights are switched on (amber-red) and is always 2 seconds. When the traffic light is amber or amber-red, the driver is still allowed to pass the traffic light.

3.5 Implementation of Time to Green and Time to Red

This part of the research method focuses on the implementation of Time to Green and Time to Red into the micro-simulation. For this implementation, VBS (officially VBScript) will be used. In order to implement Time to Green and Time to Red in a way that would be realistic, the research of van der Burgt and Greweldinger (2018) will be used as a starting point. One of those boundary conditions will be used, with another one in addition. This results in the following boundary conditions:

1. The green light cannot be delayed or skipped;
2. There will be a rigid traffic lights regulation.

In the same study by van der Burgt and Greweldinger, the number of seconds of the countdown was also investigated. In this study, the choice was made not to take this into account and to let the drivers know the entire time a traffic light has a certain colour. There is no direct behaviour linked to the countdown, only a possible different desired speed and an adjusted reaction time.

3.5.1 Scenarios regarding Time to Green and Time to Red

When a vehicle approaches a traffic light with the Time to Green or Time to Red application, there are a number of scenarios that can take place. This section explains these scenarios. The default desired speed of the vehicles is 50 km/h.

In the flowchart presented in Figure 15, an overview is given to see which scenarios could occur. The full explanation is given below the figure.

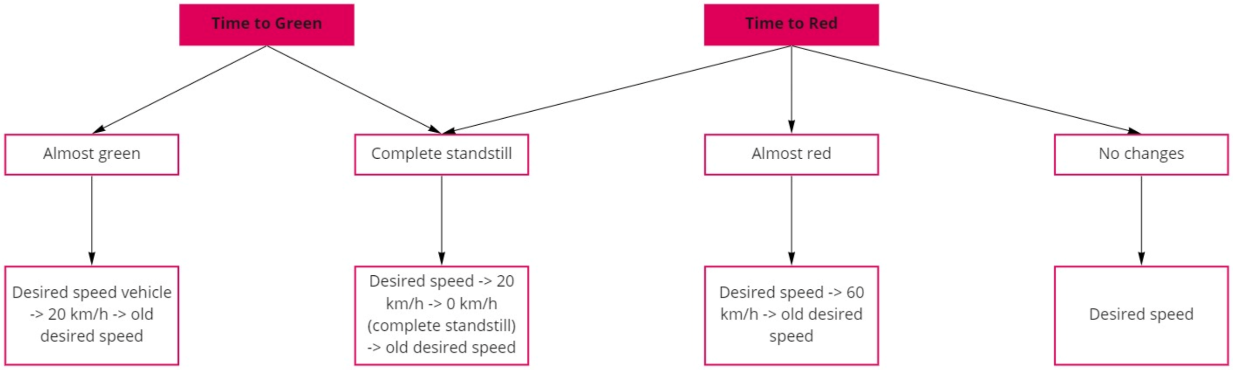

Figure 15: Flowchart of different Time to Green or Time to Red scenarios

Time to Green

Complete stop

The vehicle is approaching the traffic light and it is already known that the vehicle has to come to a complete standstill, as the light still remains red for some time. In PTV VISSIM, it is not possible to tell the driver to ease off the accelerator, so it was decided to set the desired speed to 20 km/h. In this way, the choice has been made to simulate the release of the throttle. When the light becomes green, the vehicle gets its original desired speed back.

Almost green

The vehicle approaches the traffic light and the light is still red, but in a few seconds it will turn green. The vehicle will be advised to slow down (briefly) to 20 km/h. This advice is valid until 2 seconds before the green light cycle starts. This will give the vehicle its original speed again 2 seconds before the green light, allowing the vehicle to accelerate to its original desired speed.

Time to Red

No changes

The vehicle approaches the traffic light and still has plenty of time to pass the green light. The vehicle gets to know the remaining green time, but the desired speed of the vehicle does not change.

Almost red

The vehicle approaches the traffic light and it is doubtful whether it will pass the green or amber light. This causes the desired speed to be increased to 60 km/h so that the vehicle can still make the green or amber light. The vehicle will continue at 60 km/h for as long as necessary. Once it is determined that the vehicle will make it, the vehicle will return to the previous desired speed.

Complete stop
The vehicle is approaching the traffic light and is not going to pass the green light anyway, even though the green light is still on. Just as in the case of the Time to Green 'complete stop', the vehicle will decelerate to 20 km/h. In this situation, the vehicle still has to come to a complete stop.

3.6 Implementation of behavioural characteristics

This part of the research method focuses on the implementation of the behavioural characteristics. Just as with the implementation of Time to Green and Time to Red, VBScript is also used for the implementation of the behavioural characteristics. In this research, two behavioural characteristics will be taken into account. These two are described in this section.

3.6.1 Reaction time of driver

The first one is the reaction time of a driver. The time a driver needs to react to the change of the traffic light is between 1 and 2 seconds (Suijs, 2022). Within this study, the choice was made to only look at 1 second of 'earlier' green, which should represent reducing the reaction time by 1 second. This is due to the fact that 2 seconds earlier green will probably lead to dangerous situations in real life. Also, within this study, the possible increase in evacuation time of the intersection has not been taken into account.

3.6.2 Speed behaviour

The second behavioural characteristic is linked to the different scenarios, as described in section 3.5.1. In these scenarios, it is described that in some cases the desired speed of a vehicle is adjusted for a certain period of time. Although it is an obligated change in speed in some cases, it is counted as a change in behaviour in this study.

3.7 Final model implementation

As already mentioned earlier, the implementation of the C-ITS applications in PTV VISSIM will be done by means of VBScript. PTV VISSIM will, among other things, ensure that the vehicles know where they want to go, how many vehicles are entering the network, and what kind of behaviour they show. With the piece of code from VBScript, the vehicles passing by the investigated intersection will be controlled by a possible change in desired speed. This will be based on the different scenarios as explained above.

Before it can be determined which scenario can be applied to a certain vehicle, the code will check whether it is a C-ITS vehicle or not. The difference between the different vehicle types is implemented in the code. The amount of C-ITS and non-C-ITS vehicles are entered into PTV VISSIM in percentages for the simulation. In total there are four different types:

- Not a C-ITS vehicle. The vehicle does not know what the green and red times of the traffic light are and the behaviour is not adjusted.
- A C-ITS vehicle, but not yet 'connected' with the traffic light. Only when the vehicle is within a certain range, the vehicle gets to know the red or green times and possibly a speed change.
- A Time to Red vehicle. The vehicle is told how long it will be before the traffic light turns red again. If necessary, the speed may be increased to 60 km/h.
- A Time to Green vehicle. The vehicle is informed how long it will be before the traffic light turns green again. If necessary, the speed may be decreased to 20 km/h.

If it is a C-ITS vehicle, it is checked where the vehicle is currently driving. If the vehicle is within 200 metres of the traffic light, the vehicle is told how long it will be before the next colour comes on. So if it is green, the vehicle is told how long it will be before it turns red, and vice versa. Based on this, the vehicle may temporarily be given a different desired speed.

3.8 Type of tests

There are several situations in which the model will be tested. The first run will be a baseline measurement, which means that no C-ITS vehicles will be present. In the following simulations, the percentage of C-ITS vehicles will be increased by 10%. This will probably show a point where the system will be useful. During these simulations, the model will be run 10 times on different random seeds. This is equivalent to 10 hours of simulation.

4. RESULTS

This chapter discusses the results. In the first section of this chapter, the network-wide results are presented, explaining what can be seen and why. The second section of the chapter looks at individual vehicles, and in particular the 'winners' and 'losers' of the system. In the third and final part of the chapter, the results of the statistical test are shown and explained.

In the following sections of this chapter, several measurement detectors were used in PTV VISSIM to collect the data. In the table below, an overview is given of the certain detector and the possible route.

Table 3: Overview of certain detector with possible route

Detector	Route
1	West - South
2	West - East
3	West - North
4	South - East
5	South - North
6	South - West
7	East - North
8	East - West
9	East - South
10	North - West
11	North - South
12	North - East

The routes of detectors 1, 4, 7, and 10 make a turn to the right and do not have to make use of the traffic light system of the intersection, since there is no traffic light on these turns.

4.1 Network effects

This part of the results focuses on the overall effects in the network of the C-ITS implementation. Per KPI the results will be shown. This is done using different graphs that are formed from the results. In Appendix A: Statistical Test Results the averages and standard deviations of the results of the different C-ITS percentages are presented. Furthermore, Appendix B: Results of Percentages Differences contains the tables with the percentage differences from the results the travel time, stop delay, average length of the queue, and number of stops.

4.1.1 Environment

Under the heading of environment, there are two output results, namely acceleration, and deceleration. The results are shown in Figure 16 and Figure 17.

The output that could be obtained from PTV VISSIM included the maximum and minimum acceleration per vehicle. With this, an assumption was made that the minimum acceleration represents the deceleration, and the maximum acceleration represents the acceleration. When looking at these results, this also corresponds to the pre-set maximum and desired acceleration and deceleration in PTV VISSIM. The maximum deceleration is set to -8,50 m/s^2 and the desired to -3,0 m/s^2. The maximum acceleration is set at 3,5 m/s^2 and the desired acceleration fluctuates between 0 and 3,5 m/s^2.

A striking feature of Figure 16 is that there is relatively little difference in the results regarding the different penetration rates. Based on these two peaks, a number of things become clear.

The growing peak on the right-hand side of the graph represents the acceleration of the vehicles when they are not following a vehicle. It can be seen that, in general, vehicles using Time to Red and Time to Green accelerate less quickly. This is especially noticeable in the bars between 2,04 and 3,24 m/s^2. This can also be explained by the fact that vehicles can be given an advisory speed of 20 km/h. This allows for situations where the vehicles do not have to come to a complete stop, and can therefore return to their normal desired speed (50 km/h) from 20 km/h onwards. At the peak of 3,44 and 3,64 m/s^2, it can be seen that there are several outliers, especially C-ITS percentages of 40, 50, and 100%.

The second point can be seen by looking at the peak on the left. This peak is about low accelerations, the vehicle tracking behaviour can be seen here. However, something remarkable can be seen here. This peak is divided into two peaks. The right-hand side of this part of the graph has peaks of 40, 50, and 100% C-ITS at 0,44 m/s^2, while the rest of the data has a peak at 0,24 m/s^2. Furthermore, even the measurement of 50% C-ITS has a peak at 0,64 m/s^2.

There is no explanation for the somewhat odd spots of the peaks of 40, 50, and 100% C-ITS in either cases. This will be discussed in Chapter 5 Discussion.

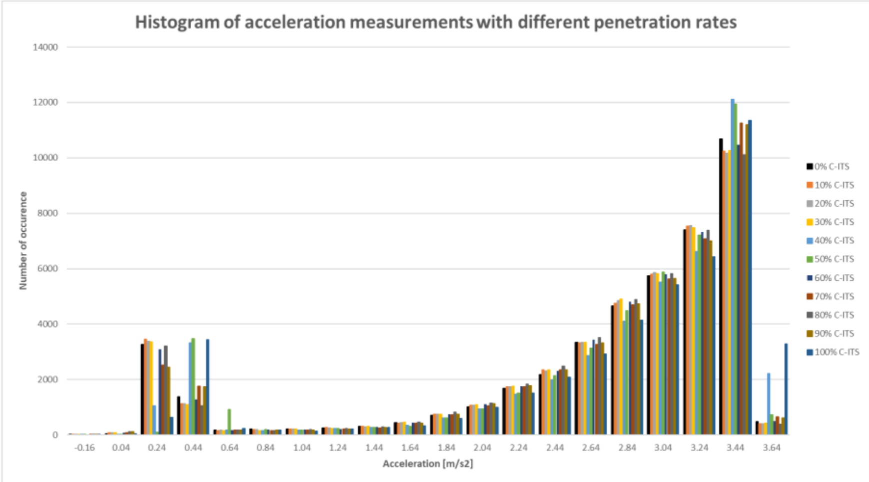

Figure 16: Histogram of acceleration measurements with different penetration rates

Regarding the deceleration graph in Figure 17, there is a lot of difference between the penetration rates of the C-ITS application. There are a few points that become clear from this graph, this is explained below.

The first remarkable thing is that the majority of vehicles brake more calmly when using the C-ITS application. This can be seen on the right side of the graph after -3,5 m/s^2. This can be explained by the fact that in the simulation the acceleration is simulated by letting the vehicles drive at 20 km/h. The vehicles may therefore brake relatively calmly to reach 20 km/h, and in the end, they do not have to brake as hard to come to a standstill.

The second thing that can be deduced from the graph is that on the left-hand side of -3,5 m/s^2 the vehicles with a C-ITS percentage of 40 or 50% have high peaks. This may be due to the fact that in these scenarios the speed differences between certain vehicles (users and non-users) are larger. This may result in the vehicles using the system being instructed to drive at 20 km/h while the non-users drive at 50 km/h.

The third and final point is that the number of vehicles braking hard increases when the system is used. This can be seen in the leftmost peak. From -7,10 to -8,20 m/s^2, it can be seen that in all scenarios the

C-ITS applications cause a harder brake. This could be due to the fact that they have been instructed to drive 60 km/h for a certain time. If it is eventually determined that they cannot achieve this, they have to brake harder than originally intended.

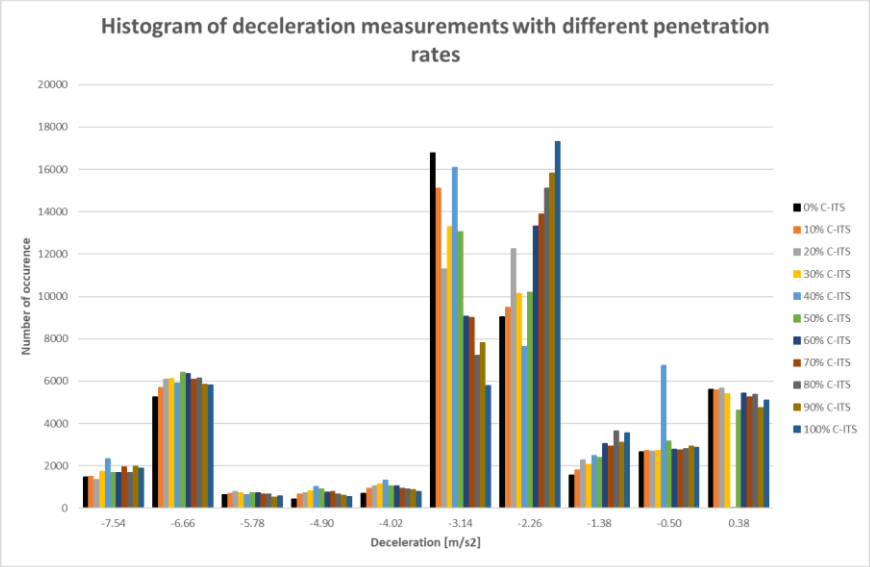

Figure 17: Histogram of deceleration measurements with different penetration rates

In conclusion, the number of vehicles that accelerate fast increases, but the number of vehicles that accelerate slower also increases. From the results of the deceleration, it can be concluded that the drivers decelerate slower. Since slower acceleration causes more emissions (Bokare & Maurya, 2013), it can be concluded that the C-ITS application has a good influence on the environment.

4.1.2 Safety

The graph with the (average) speed differences analyses whether safety has improved. Looking at the graph in Figure 18 it can be seen that there are fewer negative speed differences. Negative speed differences mean that the vehicle in front of the other drives slower. This means that it is possible that the following vehicles (suddenly) have to break (hard). Positive speed differences mean on the other hand that the following vehicle is driving slower than the vehicle in the front. In Appendix A: Statistical Test Results, Table 11, it can also be seen that the mean value of the results decreases. In conclusion, this means that the traffic situation becomes safer.

However, this finding is not entirely in line with expectations. What is expected is that speed differences at percentages 0 and 100% are equal. This is because all vehicles in these scenarios receive the same speed advice. Therefore, it would be expected that the speed differences between 40 and 60% are the highest, but this is not reflected in the results. A possible explanation for this could be that the vehicles are forced to drive 20 and 60 km/h. At these two speeds, it is not distributed, which is the case with the desired speed of 50 km/h. This means that at 50 km/h there can be (small) differences between the speeds of the vehicles, while at 20 and 60 km/h this is not the case.

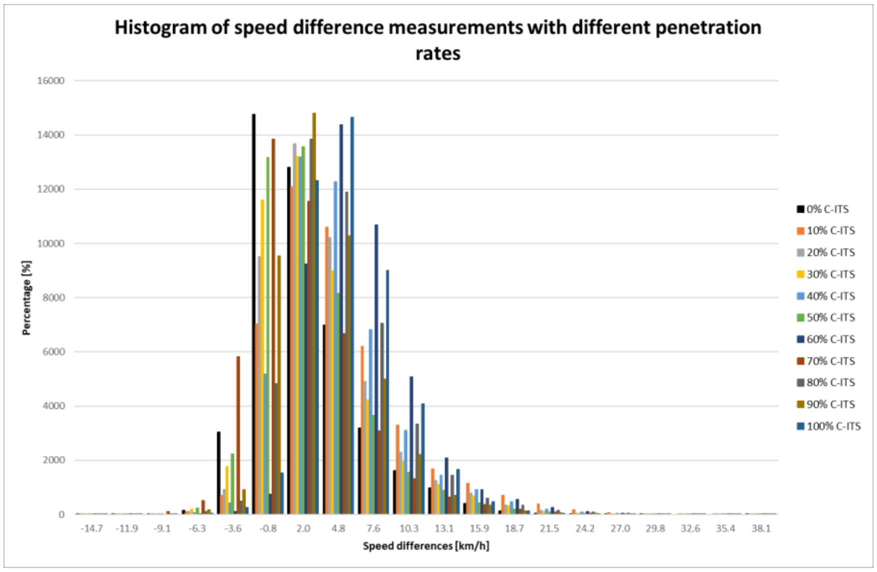

Figure 18: Histogram of speed difference measurements with different penetration rates

4.1.3 Efficiency

As mentioned before, efficiency has many output parameters. First, the average speed is explained, which can be seen in Figure 19. This graph shows how often a certain average speed occurs per C-ITS percentage. As can be seen from the graph, there is little difference between the different penetration rates. In this section of this chapter, more information about this is given.

From this graph and the results of the mean in Appendix A: Statistical Test Results, Table 12, it becomes clear that the average speed of the vehicles decreases as the percentages of C-ITS vehicles increase. Since the lines with the C-ITS application are almost always slightly slower than the line without the C-ITS application, this means that the whole traffic flow is slightly slower when using Time to Green and Time to Red. As a result, the overall travel time increases slightly. These measurements contain all the results. This means that also the measurements of the vehicle being stationary (0 km/h) are included. This is explained by the following graph, Figure 20.

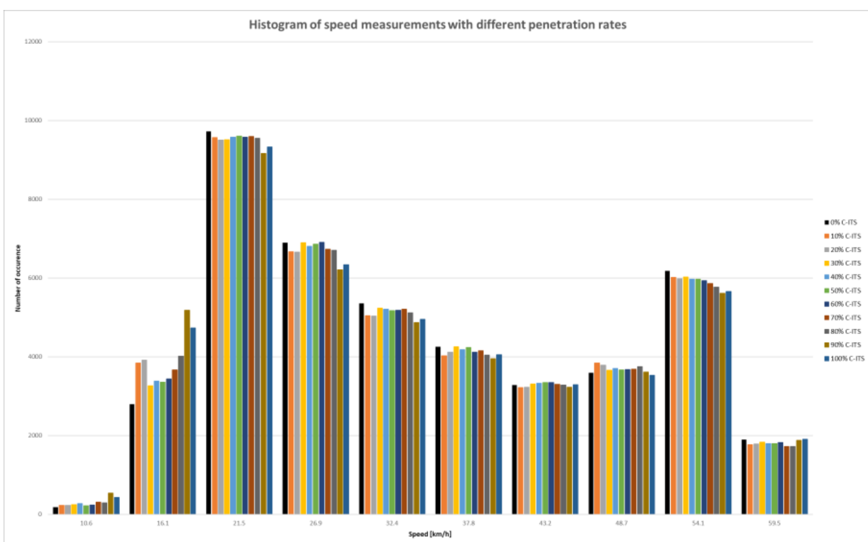

Figure 19: Histogram of speed measurements with different penetration rates

In order to determine the impact of C-ITS applications on travel time, Figure 20 is shown. This figure shows by presenting the percentages of the increase or decrease per percentage C-ITS per direction (measurement detector, Table 3). This creates a clear overview of which times are best and worst for which route. From this graph, it can be known that the travel time mainly increases. Only for routes 7, 9, and 12, it decreases a little, about 2,5% in these cases. For all other routes, travel time increases.

This increase in travel time could happen due to the way the C-ITS applications are implemented. As mentioned in the Research Method, possible speed advice is given to the C-ITS vehicles when they are within a certain range. This depends on the travel time of the car to the traffic light and how long the traffic light remains a certain colour. When a vehicle drives to the (current green) traffic light, and the travel time is larger than the time the light remains green, the vehicle gets the speed advice of 20 km/h. The non-C-ITS vehicles would still drive with the same desired speed further to the traffic light. This could cause the non-C-ITS vehicle does not have to stop while the C-ITS vehicle does. The way the C-ITS applications are implemented now, it seems to have a negative effect on travel time.

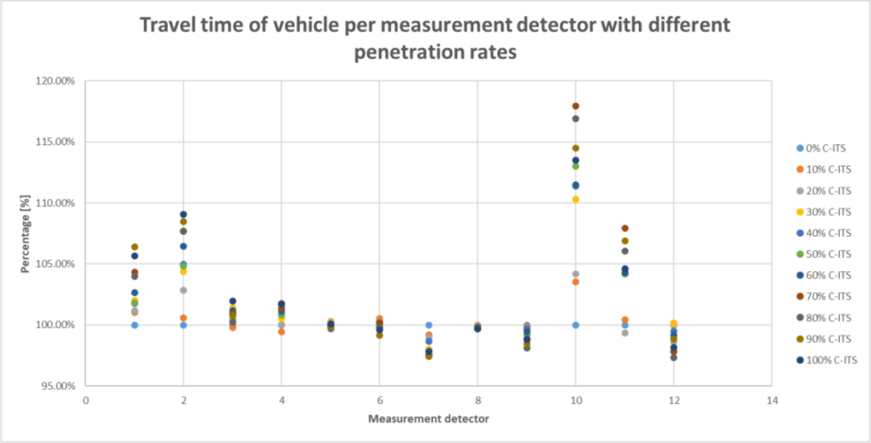

Figure 20: Travel time of vehicle per measurement detector with different penetration rates

The next thing to analyse is the stop delay of the vehicles. The corresponding graph is shown in Figure 21. This graph clearly shows that the stop delay is generally decreasing (maximum of 37,5% decrease). This is only not the case for routes 1, 4, and 10. For route 1 this is a maximum increase of 130%, route 4 a maximum of 5%, and route 10 a maximum of 80%. These are routes that turn right and thus do not use the traffic lights. As a result, they are hindered by the other vehicles. Route 7 does also not use the traffic light but performs better with more C-ITS vehicles in the network. When looking only at the vehicles that have a decrease in stop delay, it decreases by 12,5%. For the vehicles that are affected, an increase of 27,7% can be seen. In conclusion, the stop delay has quite a positive influence on traffic when C-ITS is implemented. However, this is not for everyone.

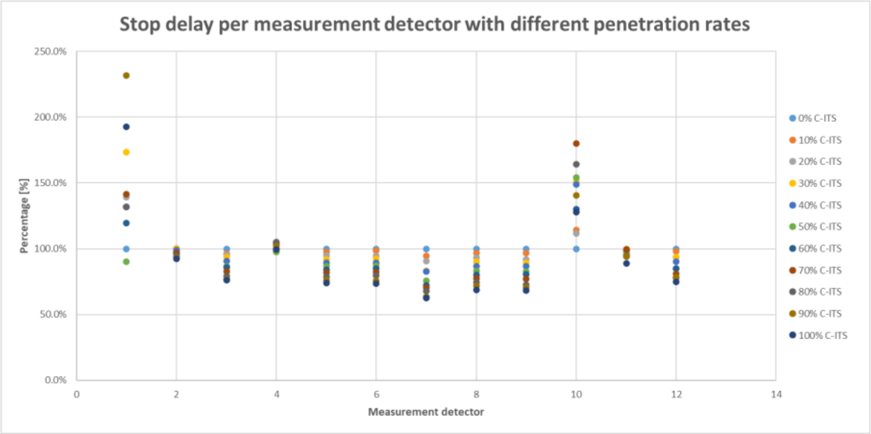

Figure 21: Stop delay per measurement detector with different penetration rates

PTV VISSIM registers a vehicle as part of a queue if the vehicle drives between 0 and 10 km/h. Figure 22 shows the average length of the queue. This graph shows very positive results in almost all directions. For the South and the East, it shows the more C-ITS vehicles in the network, the shorter the queue length. For the West side, this is almost true, expect for the 30% C-ITS. For that percentage, a small increase of 1% can be seen. In contrast, the Northern side is increasing reasonably well. From this side, the average queue length increases up to 4,2% in the case of 70% C-ITS.

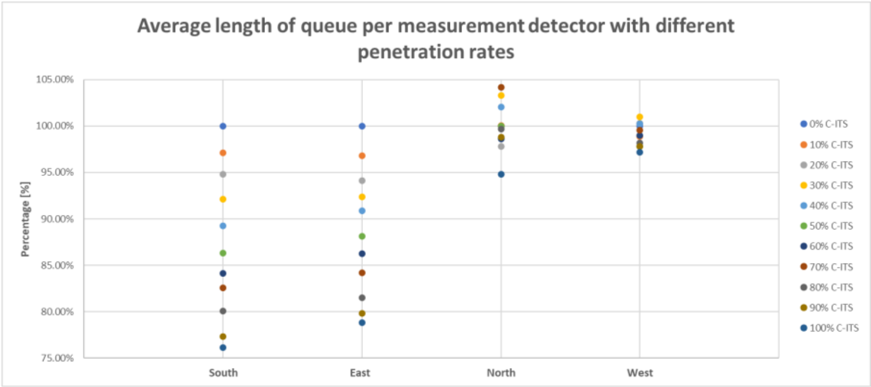

Figure 22: Length of queue per measurement detector with different penetration rates

4.1.4 Comfort of driver

The number of stops is related to the comfort of the driver. The fewer stops the driver makes, the more comfortable he/she will be driving. In Figure 23 are the results of the number of stops for the delay measurements. In the case of routes 1, 2, 4, 10, and 11 it can be seen that more C-ITS vehicles in the network does not lead to better results. This is the case for the other routes.

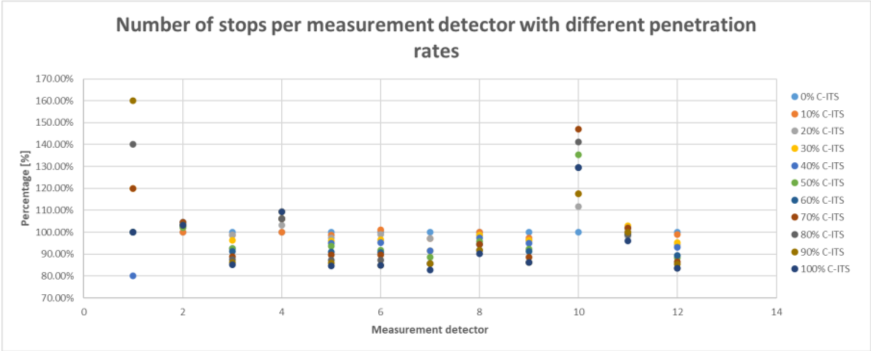

Figure 23: Number of stops per measurement detector with different penetration rates

4.2 Individual vehicles

Within the implementation of Time to Red and Time to Green, there will be 'winners' and 'losers'. The winners use the system and profit, while the losers do not use the system and also experience a lot of inconveniences.

The winners of the system are actually all the vehicles that have better results than in the 0% C-ITS situation. This is not the case for the losers. This is especially noticeable in the results of stop delay and number of stops. The graphs of these results (Figure 21 and Figure 23, respectively) show especially for the routes that do not make use of the traffic light (routes 1, 4, 7, and 10) that they do not benefit from the system. Not even in the case of 100% C-ITS. Since these vehicles do not pass a traffic light and thus do not receive any advice, it is possible that they drive behind vehicles that have received advice and anticipate this. In this situation, they are then stuck behind a vehicle and there is probably little or no possibility of them overtaking. It can be seen that in these cases, the stop delay and number of stops increase.

4.3 Statistical test

In order to validate the data, a two-sample t-test with unequal variances (also known as Welch's t-test) was performed. The t-test was chosen since with this test, it is possible to compare a population before and after some experimental intervention (Bevans, 2022). This is the case in this research since the different runs of the different scenarios have the same so-called 'common random numbers´. However, it was decided to validate the data as a whole per scenario, rather than per run per scenario. The different scenarios reflect the different C-ITS percentages (0-100%). Each scenario consists out of 10 runs, which means that the scenario has been executed 10 times. This data is equivalent to 10 hours of simulations.

It is not possible to compare the 10 runs per scenario (C-ITS percentages). This is because there are small differences in the total number of data points per run. This difference is at most 105 data points. Therefore, a paired t-test is not possible since it compares the results 1-to-1. Therefore, the choice was made for the two-sample t-test with unequal variances. This does include this difference. If all data are considered as a whole, there is still a difference between the number of data points per C-ITS percentage. In this case, the maximum is 136 data points.

The formula of the t-test is as follows:

Equation 1: Two sample t-test with unequal variances

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

In which $\bar{x}$ is the mean of the sample, s the sample standard deviation of a random sample of size n. In the case of this study, $\bar{x}, s$ and n are based on all data from all 10 runs of each scenario. This is a minimum of 44158 and a maximum of 44350 data points per scenario.

For the acceleration and speed differences, it is wanted to know whether the mean increases. Therefore, the following null hypothesis is formulated for the t-tests for these data, namely:

$$H_0: \bar{x}_1 \geq \bar{x}_2$$

This gives the following alternative hypothesis:

$$H_1: \bar{x}_1 < \bar{x}_2$$

The null hypothesis for the t-test of the average speed and deceleration is slightly different, namely:

$$H_0: \bar{x}_1 \leq \bar{x}_2$$

This gives the following alternative hypothesis:

$$H_1: \bar{x}_1 > \bar{x}_2$$

This makes all performed t-tests one-tailed. Within the study, it is especially relevant to see whether there is an increase in average speed, speed differences, and deceleration, and therefore a significant difference. For the acceleration, it would be desirable for these values to decrease and for a significant difference to be seen. Furthermore, the tests were performed with a 95% confidence interval.

The test has only been done for the data of speed, speed differences, acceleration, and deceleration, as these data sets are large and can be compared. Within the tests, each time a comparison was made between the measurement of 0% C-ITS and another percentage of C-ITS.

For each category, a table is displayed with the results of the t-test. The table with the results of the t-test contains the probability, statistic t-test, critical value of t-test, and the possible rejection of H_0. The possible rejection of H_0 contains a box for each percentage equation. If the box is checked, the H_0-hypothesis can be rejected. The mean and standard deviations of the different C-ITS percentages are also calculated. These outputs can be found in Appendix A: Statistical Test Results.

It is possible to check whether the H_0-hypothesis can be rejected by checking if the probability (P(T<=t)) is smaller than alpha, α (in this case 0.05 because of the chosen confidence interval). It is also possible to check if the results of the t-test are greater than the results of the critical area of the t-test. This critical area is for all comparisons the same, namely 1,645. Both options show the same result, but the first option is presented in percentages and the other one with the actual numbers.

4.3.1 Acceleration

Analysis of the acceleration results shows that the H_0-hypothesis cannot be rejected for all comparisons, as there is no statistical evidence for this when a 95% confidence interval is applied. As Table 4 shows, this is only the case for certain equations, such as the equation between 0 and 40, 70, 90, and 100%. For these scenarios, it can therefore be stated that within a 95% confidence interval, the acceleration average of the 0% C-ITS situation is lower than the average of the situations of 40, 70, 90, and 100%. In all other comparisons, it can be stated that within a 95% confidence interval, the acceleration average of the baseline situation is equal to or higher than the C-ITS situation.

Table 4: Results of t-test of different compared scenarios of the acceleration data

Comparison	0-10%	0-20%	0-30%	0-40%	0-50%	0-60%	0-70%	0-80%	0-90%	0-100%
P(T<=t) one-tailed	0,450	0,250	0,064	0,033	0,086	0,110	0,016	0,070	0,030	0,022
T-test results	0,125	0,673	1,520	1,836	1,368	1,226	2,133	1,475	1,871	2,010
Reject H_0	☐	☐	☐	☒	☐	☐	☒	☐	☒	☒

4.3.2 Deceleration

The analysis of the delay results, shown in Table 5, also shows that not all H_0-hypothesis can be rejected. However, it can be seen that they differ more when compared to the acceleration results, only in the comparison between 0 and 50% C-ITS this is not the case. A possible explanation for this is given in Chapter 5 Discussion. Furthermore, for the deceleration results, it can be stated that all comparisons (except for the comparison of 0 and 50% C-ITS) fall within the 95% confidence interval. Therefore, the H_0-hypothesis can be rejected, which means that the average of the 0% C-ITS situation is higher than the average of the situations with C-ITS.

Table 5: Results of t-test of different compared scenarios of the deceleration data

Comparison	0-10%	0-20%	0-30%	0-40%	0-50%	0-60%	0-70%	0-80%	0-90%	0-100%
P(T<=t) one-tailed	0,0167	0,002	0,000	0,003	0,318	0,016	5,4 * 10^{-6}	5,5 * 10^{-18}	3,4 * 10^{-32}	6 * 10^{-48}
T-test results	2,123	2,863	3,659	2,736	0,474	-2,151	-4,401	-8,565	-11,759	-14,509
Reject H_0	☒	☒	☒	☒	☐	☒	☒	☒	☒	☒

4.3.3 Speed difference

From the statistical t-test of the speed differences, it can be seen that for all comparisons the H_0-hypothesis can be rejected. This can be seen in Table 6. This means that within a 95% confidence interval it can be said that the average speed differences are smaller than in the initial situation with 0% C-ITS.

Table 6: Results of t-test of different compared scenarios of the speed difference data

Comparison	0-10%	0-20%	0-30%	0-40%	0-50%	0-60%	0-70%	0-80%	0-90%	0-100%
P(T<=t) one-tailed	0,017	1,68 * 10^{-7}	1,82 * 10^{-23}	2,01 * 10^{-50}	2,86 * 10^{-86}	4,6 * 10^{-142}	1,2 * 10^{-221}	0	0	0
T-test results	2,127	5,102	9,916	14,896	19,676	25,396	31,852	38,464	46,502	54,670
Reject H_0	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒

4.3.4 Speed

Finally, the analysis of the average speed. These results, Table 7, show that from the comparison between 0 and 30% and higher the H_0-hypotheses can be rejected. This means that within a 95% confidence interval it can be said that the average speed from 30% C-ITS onwards is lower than in the initial situation with 0% C-ITS.

Table 7: Results of t-test of different compared scenarios of the speed data

Comparison	0-10%	0-20%	0-30%	0-40%	0-50%	0-60%	0-70%	0-80%	0-90%	0-100%
P(T<=t) one-tailed	0,380	0,496	0,036	0,009	0,014	0,002	2,5 * 10^{-5}	0,000	1,2 * 10^{-5}	1,6 * 10^{-5}
T-test results	-0,304	-0,011	1,801	2,351	2,189	2,846	4,057	3,303	4,222	4,155
Reject H_0	☐	☐	☒	☒	☒	☒	☒	☒	☒	☒

4.4 Overall conclusion

The statistical test shows that not all H_0-hypotheses can be rejected. Depending on the data, it is determined whether this is possible or not. The statistical test is performed for the data on acceleration, deceleration, speed, and speed differences. In this section, the results are repeated once more.

For the acceleration, it can be stated that within a 95% confidence interval, the acceleration average of the 0% C-ITS situation is lower than the average of the 40, 70, 90, and 100% situations. For all other comparisons, it can be stated that within a 95% confidence interval, the acceleration average of the baseline situation is equal to or higher than that of the C-ITS situation.

For the deceleration, all equations (except the 0 and 50% C-ITS equation) fit within the 95% confidence interval. Therefore, the H_0-hypothesis can be rejected, which means that the average of the 0% C-ITS situation is higher than the average of the situations with C-ITS.

The t-tests of the speed differences all fit within a 95% confidence interval. Therefore, it can be stated that all average speed differences are smaller than in the baseline situation with 0% C-ITS.

For the t-test results of the speed, it can be said within a confidence interval of 95% that the average speed from 30% C-ITS onwards, is lower than in the baseline situation with 0% C-ITS

5. DISCUSSION

The results of this research should be interpreted with some caution for a number of reasons. To start with the implementation of the behaviour. Within this study, the choice was made to focus the behavioural aspect only on reaction time and speed changes of individual drivers. This was done because of the short time frame for this thesis. This does not give a complete picture of the Time to Green and Time to Red implementation regarding the behavioural aspects, since there are a lot more behavioural aspects apart from those two, such as acceleration or car-following behaviour.

In addition, when these systems would be applied in real life, people might ignore it or use it for their own benefit. Within this study, this has not been addressed, as PTV VISSIM assumes the perfect driver. When people ignore the system or only use it for their own benefit, dangerous situations can arise because the people who ignore the system might drive extra fast, which the other drivers do not expect. This was also one of the outcomes of the study of Rittger et al. (2015).

Another point related to practical application is the implementation of the situation where the traffic light is almost red. In these cases, the vehicle has to drive faster in order to possibly pass the green (or amber) cycle. Within the simulation, the speed increase is fixed at 60 km/h. In reality, vehicles will not all drive exactly 60 km/h, but more evenly distributed around this value or even higher. Furthermore, in the real world, the Time to Red and Time to Green will only indicate the time for which a certain light is still on. This can lead to dangerous situations.

The next point is about traffic light control. The traffic lights of the initial intersection were vehicle activated. This has been changed into a rigid control. This rigid scheme is based on the input of different directions and a visual aspect, such as (extremely) long waiting lines. Because of this, there are no calculations made about the green, red, and amber phases and this scheme will not be fully optimal.

Complementary to this discussion point regarding the cycle times of the traffic light, is the fact that when this is applied in reality, it will mainly be applied to vehicle-dependent traffic lights. If the traffic lights are vehicle activated, these green and red times are much more difficult to estimate. Therefore the vehicles with C-ITS application get a less good estimation of these times.

It should be noted that in PTV VISSIM, it is not possible to instruct the vehicle to release the throttle. Therefore, the assumption made in this study is that changing the desired speed to 20 km/h is approximately equivalent to releasing the throttle. However, this will not be completely correct since the vehicles in PTV VISSIM will (calmly) slow down to 20 km/h instead of actually releasing the throttle. Although it is not entirely as desired, a clear shift can be seen in the results, which shows that the vehicles are decelerating more slowly.

The last point regarding the implementation of the C-ITS applications in PTV VISSIM is about the clearance time. This has not been taken into account within the study. This can cause vehicles to drive through an amber light, but the next green cycle in another direction is already starting. This can cause vehicles to wait until the green cycle is over again, allowing them to cross. In reality, of course, it is not desirable for this to happen.

About the results, during the analysis of the acceleration measurements, it appeared that the peaks of 40, 50, and 100% were at somewhat strange points. No direct explanation for this observation was found. These peaks could indicate a wrong measurement for these 3 C-ITS percentages. It would be more logical if all peaks of 40, 50, and 100% were shifted a bit more to the left. These peaks would then coincide exactly with the data of the other peaks.

In addition to the results, the results of the travel time were also possibly somewhat plausible. The increase in the travel time could namely be due to the way the C-ITS application is implemented in the model. The non-C-ITS vehicles would drive longer at their desired speed, while the vehicles with C-ITS application would know much earlier that they would not reach the traffic light on time and would slow down to 20 km/h. It could be that the vehicles afterward could have driven through the green light, or that non-C-ITS vehicles accelerate at the end (briefly). However, no research has been done into this possible acceleration behaviour. Furthermore, it could also be that the C-ITS application is set too 'tight', causing some vehicles could have passed the green light but did not do so because of the required advice.

The last two points concern the statistical test. The statistical test was performed with four different output values of the model, acceleration, deceleration, speed, and speed differences. The deceleration test showed one strange result, namely the t-test comparing 0 and 50%. This t-test is the only one not within the confidence interval. There is no clear explanation for this. When this became known, the scenario of 50% was turned on twice more, but the outcome was exactly the same each time. Therefore, the way it looks now, it seems that at 50% C-ITS there is a bug in the model. It is possible that when the model is run with 49 or 51% C-ITS, the result suddenly does fit within the confidence interval. This was only not possible due to a lack of time.

In addition to this statical test, only from the results of the speed differences, it could be said that these are from the beginning (0% C-ITS) significant since all the null hypotheses could be rejected. From the results of the acceleration, deceleration, and speed, this could not be said. However, it is expected that when the number of runs is increased, the scenarios with the lower C-ITS percentages will also be significant.

6. CONCLUSION

This research was conducted to answer the main research question:
"What are the effects of C-ITS applications Time to Green and Time to Red on efficiency, comfort of driver, safety, and sustainability at a signalised intersection in a simulation environment?"

To answer this question, the research is subdivided into five sub-questions that will be answered first.

1. Which C-ITS applications exist, what are their functions, and what is the added value of the different systems regarding efficiency, comfort of driver, safety, and sustainability?

Three C-ITS applications are included in this research, namely Traffic Signal Countdown Timers, GLOSA, and Prioritising. The Traffic Signal Countdown Timers include Time to Red and Time to Green. The TTR and TTG systems inform drivers how long a traffic light will be red or green, GLOSA gives an advisory speed per driver, and Prioritising allows certain vehicles to be given priority, such as buses that are behind schedule.

Especially TTG, TTR, and GLOSA have the advantage that the travel time of vehicles and the number of stops should decrease. By reducing the number of stops, vehicles do not have to accelerate and brake as much. This reduces the emission of gases, which has a positive effect on the environment. Prioritising mainly benefits the means of transport that are given priority. In this case, the number of stops, emissions, and travel time for that mode of transport is reduced, but the number of stops, emissions, and travel time for the other modes of transport is increased. As for the safety of these systems, this is only known for TTR, TTG, and GLOSA. The literature study shows that Time to Red and Time to Green cause an increase in conflicts, while this is not the case for GLOSA.

In conclusion, if considering only the users of the C-ITS applications, a positive effect will be seen for driver comfort, environment, and part of efficiency. For safety, the conclusion will be positive for GLOSA, negative for Time to Green/Time to Red, and unknown for Prioritising.

2. What are behavioural characteristics of people that could have an effect on C-ITS applications?

Many behavioural characteristics could have an effect on traffic and thus on C-ITS applications. Think of fast or slow acceleration or deceleration, lane changes, (in)attentiveness of the driver, but also the driver's reaction speed and any speed changes. However, in this study, only the last two factors are taken into account as input for the model. Acceleration and deceleration will be part of the KPI environment regarding the assessment framework.

3. Which KPIs and behavioural characteristics (of sub-question 2) can be translated into criteria, such that an assessment framework can be drawn up?

In order to assess the model, 4 KPIs have been established. These are environment, safety, efficiency, and driver comfort. The environment includes two behavioural characteristics, acceleration, and deceleration. Based on the results of this, it can be estimated whether the C-ITS implementation has a positive or negative impact on the environment. Driver safety is tested on the speed differences between a vehicle and its predecessor. When the negative speed differences increase, it means that the vehicle in front is driving slower than the vehicle behind it. This means that situations could become more dangerous. This is in the case that there would be no possibility to change lanes and overtake the vehicle. Efficiency consists of several results, namely average length of the queue, stop delay, and average speed. When the length of the queue and stop delay decrease and the average speed increases, the results are positive in terms of implementation. Last is the comfort of the driver, which consists of the number of stops a vehicle has to make. If drivers have to stop less often, this is more pleasant for them.

4. How can a realistic Time to Green or Time to Red system be implemented in PTV VISSIM?

The implementation in PTV VISSIM for Time to Green and Time to Red will never be 100% equal to reality. However, the effects of the C-ITS implementation can be estimated. However, good assumptions need to be made to make the model more realistic. In this implementation, for example, two traffic lights per direction were used, so that a difference could be made between the reaction speeds of the different users and non-users.

Furthermore, different scenarios were created in case a C-ITS vehicle approaches the traffic light. In the case of Time to Green, there are two scenarios, it is almost green or the vehicle has to come to a complete standstill. In the case of Time to Red, there are three scenarios, complete standstill, no change, and almost green. Based on the position of the traffic light and the location of the vehicle, a choice was made under which scenario the vehicle fell. A possible change in speed was linked to this. In Appendix C: Time to Green & Time to Red VBScript, a part of the script is included. The given part of the script only shows one direction, while the actual script includes all four directions. This is done since the script repeats every time but with different variables.

5. What are the effects in terms of sustainability, efficiency, driver comfort, and safety when looking at network-wide and individual results?

As the results of the simulations with the different scenarios show, different effects can be seen concerning the C-ITS implementation. The full analysis of the results can be found in Chapter 4 Results. Through the analysis, different effects can be clearly seen. These are (briefly) discussed per KPI.

Network effects

Environment

In terms of environmental impact, the C-ITS implementation has a positive effect on this. Less hard braking means less fuel consumption. Slower braking means less energy is lost because vehicles do not have to come to a complete standstill as often. This means they need to accelerate less to get back up to the desired speed.

Safety

The results of the speed differences tell us that there are fewer negative speed differences. In the scenarios with a percentage of C-ITS vehicles, a shift can be seen with respect to the negative speed differences. These speed differences become positive values. This is a positive effect for the C-ITS implementation because it means that the traffic situation becomes safer.

Efficiency

To determine whether efficiency for the vehicles is increased when Time to Red and Time to Green are used, the average speed, stop delay, average queue length, and travel time were examined.

Average speed

From the results of the average speed, it appears that it decreases as the C-ITS percentage increases. The C-ITS vehicles have on average more often a speed of 20 km/h or lower. Furthermore, it can be seen that an (average) speed of 55 km/h or higher occurs more often with C-ITS vehicles. Therefore, the implementation of C-ITS has no positive effect on the average speed of vehicles.

Stop delay
The results of the stop delay show remarkable results. Delay generally decreases, except for the routes that turn right in the network, so they do not use a traffic light. Because of this, they experience annoyance from the C-ITS vehicles. In conclusion, the C-ITS application shows positive results, except for three routes.

Average queue length
The results of the average length of the queue show a very positive result with regard to the implementation. There is one direction, North, which may experience an increase of up to 4.2% (or 1.64 metres). All in all, the implementation of C-ITS has a positive effect on the average queue length.

Travel time
The results of the travel time show that it mainly increases. Only for three routers, which all turn right, the travel time decreases slightly. That in these cases is about 2.5%. For all other routes, the travel time increases. So the C-ITS implementation has a negative effect on the travel time.

Comfort of the driver
The final KPI is driver comfort. This KPI contains the output of the number of stops. These results show that several routes are disadvantaged. These are mainly routes where vehicles go from West to East, North to South, or want to turn right, so do not use the traffic light. For the rest, the number of stops of the drivers decreases, which is positive for the effect of the C-ITS implementation.

Individual vehicles
The vehicles that have profited from the system are actually all the vehicles that have better results than in the 0% C-ITS situation. This is not the case for the ‘losers’. As discussed above at the driver comfort and stop delay, the number of stops and the stop delay increases for several routes. These are mainly the routes that turn right, travel from West to East, and travel from North to South. Due to the fact that vehicles want to turn right, they can be delayed by getting stuck behind a C-ITS vehicle that has been given a 20 km/h speed reduction.

Overall conclusion
In conclusion, this thesis tried to find an answer to the question: "What are the effects of C-ITS applications Time to Green and Time to Red on efficiency, comfort of driver, safety, and sustainability at a signalised intersection in a simulation environment?". The micro-simulation programme PTV VISSIM was used for this purpose. The effects of the implementation of Time to Red and Time to Green have been mapped through various KPIs. In Table 8 an overview is made of the different KPIs with the different parameters that belong to them. It is also indicated per parameter whether the effects are positive or negative when Time to Red or Time to Green is active.

Table 8: Overview of effects of implementation Time to Green and Time to Red regarding the KPIs

KPI	Parameter	Positive or negative effect
Environment	Acceleration	Positive
	Deceleration	Positive
Safety	Speed differences	Positive
Efficiency	Average speed	Negative

	Stop delay	Positive for most of the routes
	Average queue length	Positive
	Travel time	Negative
Comfort of the driver	Number of stops	Positive for most of the routes

7. RECOMMENDATIONS

The first recommendation is to look more closely at the statistical part of this study. In this study, a t-test with unequal variances was performed because the data were paired. This is due to the fact that the same random seed was used for each scenario, which made it possible to compare these data. However, my knowledge of statistics is not good enough to say for sure that this was the best statistical test. Therefore, a follow-up study that also includes a statistical test would give more certainty about the results.

Secondly, this research has been done with the traffic light system of Sweden. This differs from the Dutch system. The Swedish system has an extra step between red and green that the Dutch system does not have, namely amber-red. This means that the people using the Swedish traffic lights are more likely to be told that it will be green again in a few seconds. Because of this, a follow-up study will be necessary to also determine the effects of the Dutch traffic light.

Thirdly, when analysing the data, no distinction was made between the various vehicle types. As a result, the average of all vehicles of a certain C-ITS percentage was taken, and it is unknown how much change there is between users and non-users and how these two groups react to each other. A follow-up study that does make a distinction between these two groups will provide a clearer picture of this point.

Fourthly, this study has made a number of assumptions regarding the reaction time and maximum speed of C-ITS vehicles, namely 1 second 'gain' for the reaction time and 60 km/h for the speed. This has not been varied but it is possible to investigate this further, for example by looking at the effects of a reaction time of 2 seconds 'gain' and a speed of 70 km/h.

Fifth, the literature review mentions the study by Limanond et al. (2009). This study claims that countdown traffic lights make a gain in the capacity of 0.5-1 extra vehicle per cycle. This claim has not been validated in this research. It would be interesting to do so in a follow-up study.

Lastly, this study only looked at what the effects are when Time to Green and Time to Red are implemented. Due to a lack of time, it was not possible to split up the C-ITS applications and evaluate these results. Because of this, it is now not clear what the effects are of only Time to Red or only Time to Green. A follow-up study can clarify this.

8. BIBLIOGRAPHY

Aghabayk, K., Sarvi, M., Young, W., & Kautzsch, L. (2013). A novel methodology for evolutionary calibration of VISSIM by multi-threading. *Australasian Transport Research Forum*.

Ahn, K., Rakha, H., Trani, A., & & Van Aerde, M. (2002). Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. *Journal of transportation engineering 128 (2)*, 182-190.

Bevans, R. (2022, May 23). *An Introduction to T-Tests | Definitions, Formula and Examples*. Retrieved from Scribbr: https://www.scribbr.com/statistics/t-test/

Bokare, P. S., & Maurya, A. K. (2013). Study of effect of speed, acceleration and deceleration of small petrol car on its tail pipe emission. *International Journal for Traffic and Transport Engineering*, 465-478.

Chen, I. C. (2007). *The Impact Evaluation of Vehicular Signal Countdown Displays.* Taiwan: Institute of Transportation, Ministry of Transportation and Communications.

Eurostat, Statistics Explained. (2021, June 3). *Stock of vehicles at regional level*. Retrieved from Eurostat, Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Stock_of_vehicles_at_regional_level#Regional_characteristics_within_the_EU

Gajananan, K., Sontisirikit, S., Zhang, J., Miska, M., Chung, E., Guha, S., & Prendinger, H. (2013). A Cooperative ITS study on green light optimisation using an integrated Traffic, Driving, and Communication Simulator. *Australasian Transport Research Forum 2013 Proceedings* .

Google. (2022). *Uppsala*. Retrieved from Google Maps.

Goudappel, & Rise. (2022).

Harms, H. (2018). *Fietsvriendelijke verkeersregeling: Evaluatie onderzoek.* Provincie Noord-Brabant.

HCM. (2010). *Highway Capacity Manual.* Washington, D.C.: Transportation Research Board.

Karabag, H., Ulak, B., Mjogolo, F., Kidando, E., Ozguven, E., Sando, T., & Moses, R. (2020). Estimating the impact of Green Light Optimized Speed Advisory (GLOSA) on exhaust emissions through the integration of VISSIM and MOVES. *Advances in Transportation Studies: an international Journal*, 5-22.

Krukowicz, T., Firlag, K., Suda, J., & Czerlinski, M. (2021). Analysis of the Impact of Countdown Signal Timers on Driving Behavior and Road. *Energies* , 7081.

Laagland, J. (2007). *How To Model Aggressice Behavior in Traffic simulation.* Enschede.

Limanond, T., Chookerd, S., & Roubtonglang, N. (2009). Effects of countdown timers on queue discharge characteristics of through movement at a signalized intersection. *Transportation Research Part C: Emerging Technologies*, 662-671.

Mellegård, N., & Reichenberg, F. (2020). The Day 1 C-ITS Application Green Light Optimal Speed Advisory - A Mapping Study. *Transportation Research Procedia* , 170-182.

Olaverri-Monreal, C., Errea-Moreno, J., & Díaz-Álvarez, A. (2018). Implementation and Evaluation of a Traffic Light Assistance System Based on V2I Communication in a Simulation Framework. *Journal of Advanced Transportation*, 1-11.

Preuk, K. S. (2016). Does surrounding traffic benefit from an assisted driver with traffic light assistance system? *Transportation Research Part F: Traffic Psychology and Behaviour, 43*, 302-314.

Provincie Noord-Holland. (2020). *Eindrapportage, Pilot 4G5.* Provincie Noord-Holland.

Rabiul Islam, M. (2014). *Safety and Efficiency Benefits of Traffic Signal Countdown Timers: A Driving Simulator Study.* Oregon: Oregon State University.

Rittger, L., Muehlbacher, D., Maag, C., & Kiesel, A. (2015). Anger and bother experience when driving with a traffic assistant: A multi-driver simulator study. *Proceedings of the Human Factors and Ergonomics Society Europe*, 41-51.

Sánchez, M., Cano, J.-C., & Kim, D. (2006). Predicting Traffic lights to Improve Urban Traffic Fuel Consumption. In G. Wen, S. Komaki, P. Fan, & G. Landrac, *2006 6th International Conference on ITS Telecommunications Proceedings* (pp. 331-336). Chengdu, China.

SmartCitiesWorld News Team. (2017, December 17). *'Smart' intersection aims to increase safety*. Retrieved from SmartCitiesWorld: https://www.smartcitiesworld.net/news/news/smart-intersection-aims-to-increase-safety-2422

Sokolov, V., Imran, M., Etherington, D., Karbowski, D., & Rousseau, A. (2018). Effects of Predictive Real-Time Traffic Signal Information. *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, 1834-1839.

Stevanovic, A., Stevanovic, J., & Kergaye, C. (2013). Green Light Optimized Speed Advisory Systems: Impact of Signal Phasing Information Accuracy. *Transportation Research Record*, 53-59.

Suijs, L. (2022, May 23). Wekelijks bijpraten afstuderen Welmoed. (W. Spanjer, Interviewer)

Suzuki, H., & Marumo, Y. (2020). Safety Evaluation of Green Light Optimal Speed Advisory (GLOSA) System in Real-World Signalized Intersection. *Journal of Robotics and Mechatronics 32 (3)*, 598-604.

Tertoolen, G., & Ruijs, K. (2015). *Factsheet Roodlichtnegatie.* Kennisplatform Crow.

van der Burgt, G., & Greweldinger, E. (2018). Onderzoek naar de effecten van de Afteller in ‘s-Hertogenbosch. *Verkeerskunde*, 16-17.

Vitronic. (n.d.). *Intelligent Traffic Management: Smart Solutions for Tomorrow's Cities*. Retrieved from Vitronic: https://www.vitronic.com/en-us/traffic-technology/intelligent-traffic-management

Wahlstedt, J. (2014). *Evaluation of bus priority stategies in coordinated traffic signal systems.* Stockholm: KTH Royal Institute of Technology.

Wang, K., Dixon, K., Li, H., & Ogle, J. (2004, January 1). Normal Acceleration Behavior of Passenger Vehicles Starting from Rest at All-Way Stop-Controlled Intersections. *ransportation Research Record*, pp. 158-166.

Yuan, L., Zhang, Q., & Lei, Z. (2009). Impact of Traffic Signal Countdown Displays on Driver Behaviors. *International Conference on Transportation Engineering 2009.* Chengdu.

Zhang, C., Ma, Y., & Lu, J. (2012). Study on Start-Up Lost Time of Traffic Signals with Countdown Display and the Driving Behavior at the End of Green Signal. *Proceedings of the 12th International Conference of Transportation Professionals (CICTP 2012).* Beijing.

APPENDIX A: STATISTICAL TEST RESULTS

This part of the appendix shows the averages and standard deviations of the measurements. The tables show the different C-ITS percentages of the different data, such as acceleration, deceleration, speed, and speed differences.

Table 9: Mean and standard deviation of different scenarios of the acceleration data

C-ITS percentage	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Mean	2,560	2,561	2,564	2,570	2,572	2,569	2,568	2,574	2,570	2,572	2,573
Standard deviation	0,960	0,957	0,952	0,946	0,944	0,942	0,942	0,937	0,936	0,933	0,928

Table 10: Mean and standard deviation of different scenarios of the deceleration data

C-ITS percentage	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Mean	-3,371	-3,401	-3,412	-3,423	-3,410	-3,378	-3,340	-3,307	-3,247	-3,201	-3,161
Standard deviation	2,074	2,132	2,166	2,198	2,221	2,233	2,239	2,237	2,232	2,218	2,217

Table 11: Mean and standard deviation of different scenarios of the speed difference data

C-ITS percentage	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Mean	5,491	5,423	5,328	5,177	5,023	4,878	4,708	4,524	4,343	4,134	3,939
Standard deviation	4,780	4,736	4,695	4,626	4,553	4,468	4,370	4,228	4,061	3,845	3,570

Table 12: Mean and standard deviation of different scenarios of the speed data

C-ITS percentage	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Mean	32,153	32,180	32,154	31,995	31,946	31,961	31,903	31,796	31,863	31,782	31,789
Standard deviation	13,057	13,065	13,039	13,079	13,070	13,042	13,061	13,065	13,035	13,032	12,991

APPENDIX B: RESULTS OF PERCENTAGES DIFFERENCES

This part of the appendix shows the tables of from which the travel time, stop delay, average length of queue, and number of stops graphs are made. By using the colour scheme, a clear visual aspect is added. This way it is more easy to see which directions and which C-ITS percentage results are good and less good.

Table 13: Table with travel time results per measurement detector with different penetration rates

Measurment detector	0% C-ITS	10% C-ITS	20% C-ITS	30% C-ITS	40% C-ITS	50% C-ITS	60% C-ITS	70% C-ITS	80% C-ITS	90% C-ITS	100% C-ITS
1	100.00%	101.04%	101.16%	102.01%	101.78%	101.82%	102.67%	104.33%	103.98%	106.38%	105.64%
2	100.00%	100.60%	102.84%	104.36%	104.96%	104.81%	106.44%	107.70%	107.70%	108.45%	109.05%
3	100.00%	99.82%	101.02%	101.45%	100.81%	100.50%	101.19%	100.91%	100.24%	100.76%	101.95%
4	100.00%	99.46%	100.04%	100.54%	100.83%	100.83%	101.12%	101.37%	101.66%	101.75%	101.71%
5	100.00%	100.29%	100.24%	100.18%	100.11%	99.96%	99.87%	99.95%	99.71%	99.91%	100.09%
6	100.00%	100.53%	100.31%	100.25%	99.82%	99.84%	100.21%	100.20%	99.80%	99.14%	99.61%
7	100.00%	99.21%	98.97%	98.00%	98.65%	97.86%	97.48%	97.59%	97.54%	97.43%	97.81%
8	100.00%	99.93%	99.86%	99.89%	99.84%	99.72%	99.72%	99.81%	99.75%	99.72%	99.70%
9	100.00%	99.86%	99.21%	99.62%	99.71%	99.23%	99.45%	98.85%	98.14%	98.48%	98.81%
10	100.00%	103.55%	104.17%	110.30%	111.40%	112.99%	111.47%	117.95%	116.91%	114.50%	113.50%
11	100.00%	100.46%	99.37%	104.16%	104.65%	104.16%	104.29%	107.92%	106.07%	106.88%	104.56%
12	100.00%	100.15%	98.63%	100.07%	99.48%	97.85%	99.16%	97.85%	97.32%	98.87%	98.18%
Mean	**100.00%**	**100.41%**	**100.48%**	**101.74%**	**101.84%**	**101.63%**	**101.92%**	**102.87%**	**102.40%**	**102.69%**	**102.55%**

Table 14: Table with stop delay results per measurement detector with different penetration rates

Measurement detector	0% C-ITS	10% C-ITS	20% C-ITS	30% C-ITS	40% C-ITS	50% C-ITS	60% C-ITS	70% C-ITS	80% C-ITS	90% C-ITS	100% C-ITS
1	100.0%	131.7%	139.0%	173.2%	131.7%	90.2%	119.5%	141.5%	131.7%	231.7%	192.7%
2	100.0%	98.6%	100.1%	100.3%	99.0%	96.1%	96.7%	96.8%	94.6%	93.4%	92.2%
3	100.0%	96.1%	95.6%	93.9%	90.5%	86.5%	85.8%	82.9%	79.2%	76.9%	76.4%
4	100.0%	97.7%	98.2%	100.0%	100.0%	97.7%	104.5%	103.2%	105.0%	101.8%	99.5%
5	100.0%	97.5%	95.0%	92.0%	89.5%	86.5%	84.0%	81.7%	79.0%	76.3%	74.1%
6	100.0%	98.4%	94.6%	92.2%	89.3%	86.9%	85.0%	82.5%	79.4%	75.8%	73.6%
7	100.0%	94.4%	90.5%	83.1%	82.6%	75.7%	72.3%	70.3%	67.7%	63.6%	62.5%
8	100.0%	96.7%	93.2%	90.0%	86.6%	83.1%	80.2%	77.4%	74.6%	71.7%	68.5%
9	100.0%	97.0%	92.0%	89.5%	86.6%	82.7%	80.6%	76.9%	72.6%	70.4%	68.2%
10	100.0%	114.2%	111.5%	151.2%	148.8%	153.9%	129.8%	180.0%	164.4%	140.7%	127.8%
11	100.0%	98.0%	94.1%	99.8%	99.1%	96.2%	94.7%	99.2%	94.4%	94.2%	88.8%
12	100.0%	98.1%	93.5%	93.5%	90.1%	85.1%	85.1%	80.9%	78.0%	78.2%	74.7%
Mean	100.0%	101.5%	99.8%	104.9%	99.5%	93.4%	93.2%	97.8%	93.4%	97.9%	91.6%

Table 15: Table with average length of queue results per measurement detector with different penetration rates

Direction	0% C-ITS	10% C-ITS	20% C-ITS	30% C-ITS	40% C-ITS	50% C-ITS	60% C-ITS	70% C-ITS	80% C-ITS	90% C-ITS	100% C-ITS
South	100.00%	97.14%	94.77%	92.11%	89.25%	86.29%	84.12%	82.54%	80.08%	77.32%	76.13%
East	100.00%	96.80%	94.13%	92.35%	90.89%	88.14%	86.24%	84.18%	81.51%	79.81%	78.79%
North	100.00%	100.03%	97.78%	103.27%	102.04%	99.97%	98.62%	104.19%	99.67%	98.82%	94.79%
West	100.00%	98.85%	100.27%	100.96%	100.23%	97.81%	99.00%	99.58%	98.20%	97.81%	97.20%
Mean	100.00%	98.20%	96.74%	97.17%	95.60%	93.06%	92.00%	92.62%	89.86%	88.44%	86.73%

Table 16: Table with number of stops results per measurement detector with different penetration rates

Measurement detector	0% C-ITS	10% C-ITS	20% C-ITS	30% C-ITS	40% C-ITS	50% C-ITS	60% C-ITS	70% C-ITS	80% C-ITS	90% C-ITS	100% C-ITS
1	100.00%	100.00%	100.00%	120.00%	80.00%	100.00%	100.00%	120.00%	140.00%	160.00%	100.00%
2	100.00%	100.00%	102.20%	103.30%	103.30%	102.20%	104.40%	104.40%	103.30%	103.30%	103.30%
3	100.00%	98.75%	98.75%	96.25%	92.50%	92.50%	91.25%	88.75%	87.50%	86.25%	85.00%
4	100.00%	100.00%	103.13%	106.25%	106.25%	106.25%	106.25%	106.25%	106.25%	109.38%	109.38%
5	100.00%	98.72%	97.44%	96.15%	94.87%	93.59%	91.03%	89.74%	87.18%	85.90%	84.62%
6	100.00%	101.16%	98.84%	96.51%	95.35%	91.86%	90.70%	89.53%	87.21%	84.88%	84.88%
7	100.00%	97.14%	97.14%	91.43%	91.43%	88.57%	85.71%	85.71%	85.71%	85.71%	82.86%
8	100.00%	100.00%	98.61%	98.61%	97.22%	95.83%	94.44%	94.44%	91.67%	91.67%	90.28%
9	100.00%	97.47%	96.20%	96.20%	94.94%	92.41%	91.14%	88.61%	86.08%	86.08%	86.08%
10	100.00%	117.65%	111.76%	129.41%	129.41%	135.29%	129.41%	147.06%	141.18%	117.65%	129.41%
11	100.00%	100.00%	98.02%	102.97%	101.98%	99.01%	99.01%	101.98%	99.01%	100.00%	96.04%
12	100.00%	99.03%	94.17%	95.15%	93.20%	88.35%	89.32%	86.41%	83.50%	85.44%	83.50%
Mean	100.00%	100.83%	99.69%	102.69%	98.37%	98.82%	97.72%	100.24%	99.88%	99.69%	94.61%

APPENDIX C: TIME TO GREEN & TIME TO RED VBSCRIPT

The appendix only shows a part of the complete script. This part is only for one of the routes on the West side of the intersection within the network. This is done because the script constantly repeats itself but with different parameters.

```
' Signal group 1 & 2 (west side) and creating the right time for the timers
Timer_SG1_green = cycle_time - cycle_sec - 3.1
Timer_SG1_red = cycle_time - cycle_sec - 90

If Timer_SG1_green <= 0 Then
    Timer_SG1_green = Timer_SG1_green + 110.9
End If

If Timer_SG1_red <= 0 Then
    Timer_SG1_red = Timer_SG1_red + 110.9
End If


' Check if there are vehicles in the network and receiving certain data about these vehicles
For Each vehicle In Vissim.Net.Vehicles
    vehNo = vehicle.AttValue("No")
    vehType = vehicle.AttValue("VehType")
    vehSpeed = vehicle.AttValue("Speed")
    vehPos = vehicle.AttValue("Pos")
    vehLink = vehicle.AttValue("Link")
    TravelTime_Car_TL_West = vehicle.AttValue("Time_Till_Traffic_Light_West")
    desSpeedCur = vehicle.AttValue("DesSpeed")

    RouteDecNo = vehicle.AttValue("RouteDecNo")
    RouteNumber = vehicle.AttValue("RouteNumber")

    ' Filter for C-ITS vehicles, VehType 110 is a non connected C-ITS vehicle, 120 Time to Green vehicle, 130 Time to Red vehicle
    If vehicle.AttValue("VehType") = 110 Or vehicle.AttValue("VehType") = 120 Or vehicle.AttValue("VehType") = 130 Then
        Set Veh_CITS_Attributes = Vissim.Net.Vehicles

        ' Receiving certain data about the current C-ITS vehicles in the network
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("RouteDecNo") = RouteDecNo
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("RouteNumber") = RouteNo
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("CITS_message_origin") = vehPos
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeedCur") = desSpeedCur
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("Timer_red") = Timer_SG1_red
        Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("Timer_green") = Timer_SG1_green

        ' Safe the old desired speed of the C-ITS vehicles
        If Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeedOld") = 0 Then
            DesSpeedOld = desSpeedCur
            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeedOld") = desSpeedOld
        End If

        ' Creating a filter for the different available routes in the network (in order to avoid a possible change of speed for the right turning vehicles)
        If RouteDecNo = 5 Then
            If RouteNumber = 13 or RouteNumber = 14 or RouteNumber = 20 or RouteNumber = 21 or RouteNumber = 22 or RouteNumber = 23 or RouteNumber = 24 or RouteNumber = 25 or RouteNumber = 26 Then
                If vehLink = 17 Then

                    ' Set back original desired speed of Time to Red cars
                    If vehicle.AttValue("VehType") = 120 Then
                        If (vehLink = 17 or vehLink = 10015 or vehLink = 9556 or vehLink = 10055 or vehLink = 10005 or vehLink = 9555 or vehLink = 10054) ...
                            And Vissim.Net.signalControllers.ItemByKey(4).SGs.ItemByKey(1).AttValue("SigState") <> "RED" Then
                                Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeed") = Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("desSpeedOld")
                        End If
                    End If

                    ' The vehicle is within the 200 meter range (determined with the position of the traffic light and a detector)
                    If PosDet_1 < vehPos and vehPos < PosSH_101 Then
                        ' Almost green scenario, the vehicles get 2 seconds before the traffic light turns green the original desired speed back
                        If Timer_SG1_green => 0 and Timer_SG1_green =< 2 Then
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("VehType") = 130                ' visible connection is made between vehicle & traffic light
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("CITS_Message") = Timer_SG1_green & " seconds till green"
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeed") = Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("desSpeedOld")

                        ' Time to Red scenario, there is no change in desired speed of the vehicles since they have enough time
                        Elseif Timer_SG1_red =< 24 and TravelTime_Car_TL_West < Timer_SG1_red Then
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("VehType") = 130                ' visible connection is made between vehicle & traffic light
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("CITS_Message") = Timer_SG1_red & " seconds till red"
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeed") = Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("desSpeedOld")

                        ' Almost red scenario, it is doubtful whether the vehicle can go through the green light, which causes an increase in desired speed
                        Elseif Timer_SG1_red => 13 and Timer_SG1_red <= 18 and (Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("VehType") = 120 or Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("VehType") = 130) Then
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeed") = 60

                        ' Time to Green scenario, the traffic light stays red for quite some time, so the vehicles gets to release the throttle
                        Elseif TravelTime_Car_TL_West <= 10 or Timer_SG1_red => 24 Then
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("VehType") = 120                ' visible connection is made between vehicle & traffic light
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("CITS_Message") = Timer_SG1_green & " seconds till green"
                            Vissim.Net.Vehicles.ItemByKey(vehNo).AttValue("DesSpeed") = 20
                        End If
                    End If
                End If
            End if
        End If
    End If
Next
```