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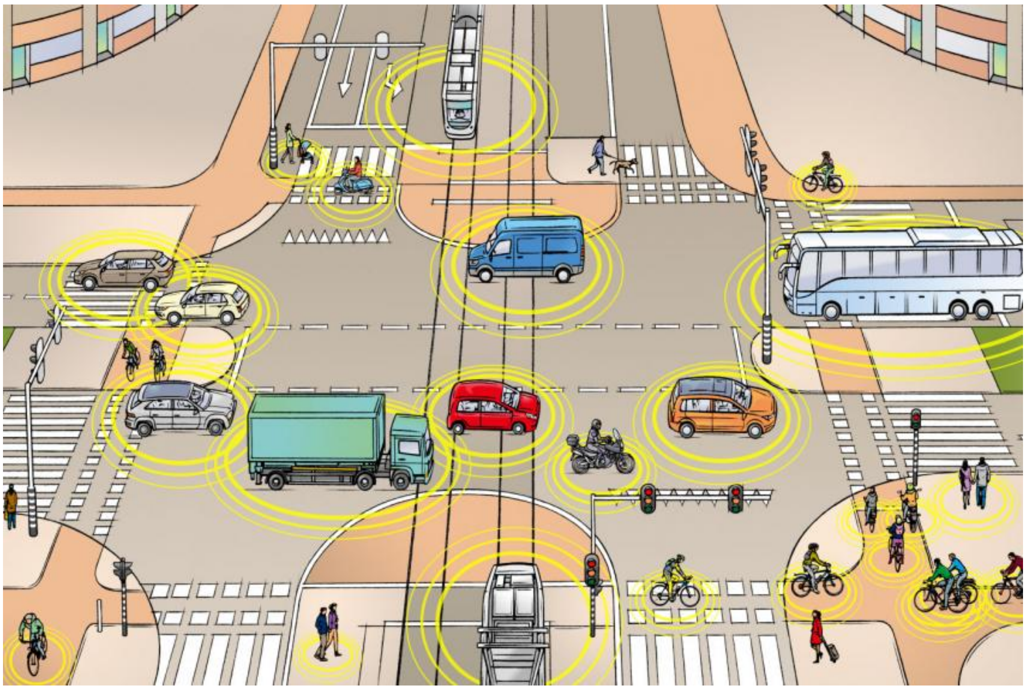
Bachelor Thesis

Minimizing Freight Traffic Disturbances in Almelo :

An analysis of conditional priority strategies and impacts



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Executive Summary

Minimizing Freight Traffic Disturbances in Almelo

by Geraldo ÇYRBJA

The growing freight movement in urban areas can be considered one of the major traffic challenges in the near future. The increasing movement of freight causes traffic congestion, which affects the flow of both private and heavy-duty vehicles. Therefore, it is crucial to develop effective traffic management strategies in multimodal corridors that carry a lot of freight traffic. The main issues for this category of traffic are the delays and the stops in the queues which are directly related to increased energy costs and carbon emissions. The main goal of this research is to develop freight traffic prioritization strategies that aim to decrease the travel time and number of stops of these heavy-duty vehicles across two intersections in an urban corridor in Almelo's ring road. The research focuses on constructing prioritization algorithms for the traffic control system. The developed priority scenarios include absolute priority, priority with a recovery cycle, and conditional (platooning) strategy. The conditional priority makes use of synchronization between two consecutive intersections to start a green wave that prioritizes a convoy of trucks accumulated at the previous junction.

Evaluating the proposed interventions using a simulation software provided very interesting results regarding the travel time and queue as stops performance indicators. The results showed that absolute priority is not beneficial for the whole traffic as it causes too many disruptions on the other directions of travel due to assigning most of the green time to the prioritized direction, even though it improves the flow of trucks significantly. The priority with a recovery cycle achieved the best performance among all the interventions during off-peak period (low demand scenario) by lowering the stops and the travel time in the prioritized direction substantially while causing little effect on the average travel time of the first junction and reducing the average stops per vehicle of both intersections. The conditional (platooning) strategy resulted very beneficial during the peak period (high-demand scenario). It reduced the travel time of the trucks in the prioritized direction by 23 % in average while only causing a negligible increase on the travel time of the whole first intersection. On the other hand, the average stops were reduced significantly for the priority route, as well as for both junctions in general. The results suggest that the conditional priority strategy is effective in decreasing the disturbances of freight traffic in urban intersections, but some implications are further discussed in the report.

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Chapter 1

Introduction

In the recent years of global industry expansion, there has been growing interest in the development of strategies to make freight transportation in urban areas more sustainable and efficient. The shipment of goods by trucks and other heavy-duty vehicles is of great importance to many sectors of the economy, such as manufacturing, retail, and construction. However, the continuous increase in volume of freight traffic on urban roads has led to congestion and delays that can have significant economic and environmental impacts. Some consequences of traffic delays include: increase the cost of goods and services, reduce efficiency, and increase emissions of air pollutants and greenhouse gases.

Currently, many transportation specialists are working on providing solutions to the freight traffic efficiency issue. Using prioritization techniques that give heavy-duty vehicles priority at signalized junctions is one possible tool used for the improvement of travel time and energy consumption efficiency. Intelligent transportation technologies, signal synchronization integrated with dedicated lanes for freight vehicles are a few examples of prioritization strategies. These initiatives seek to lessen congestion and delays, increase the efficiency of goods transportation, and increase the sustainability of urban freight transport by reducing the energy and time loss of these large vehicles due to a large number of stops and waiting times in urban intersections.

However, the implementation of such strategies comes with numerous challenges since prioritizing certain directions or classes of vehicles can cause disruptions or delays for other vehicles, such as cars, bikes, public transport or other directions which are not prioritized and worsen the traffic flow in general. On the other hand, trucks and trailers are large means of transport that require more time to perform maneuvers such as accelerating/decelerating than small passenger vehicles, so the implementation of a proper priority strategy may improve the traffic conditions in general also for other vehicles. In addition, the effectiveness of these strategies may depend on many factors, including traffic volume, vehicle composition, transportation culture and the characteristics of the surrounding road network. The situation becomes even more complex due to high competition for priority of different road users like emergency vehicles and public transport. The ambulances and fire trucks for example are entitled to absolute priority in order to respond to urgencies and buses may also request priority to be able to follow their schedule.

The construction of an efficient prioritization strategy involves taking into account many situational-specific complications such as: the directional demand distribution within the intersection, traffic composition, and variation of traffic attributes during different times of the day. Therefore, the design process aimed to benefit not only the targetted group of vehicles but also the traffic conditions in general at the junction is more complex than giving priority to each truck arriving at the intersection. Several conditions and factors need to be assessed when a traffic light cycle is modified by extending the green time or truncating the red time in order to grant a priority to a direction. Having some type of prediction for the number of trucks that are approaching the intersection is a very decisive factor as it might be more efficient for the whole traffic to have a number of trucks in the queue before starting a green wave along multiple intersections because it is not always possible to grant immediate priority to every single truck arriving. To summarize, the core of the study will be the prioritization of heavy-duty vehicles at two consecutive signalized intersections with high freight traffic composition in Almelo, Netherlands, while satisfying multiple conditions to avoid causing other road users disruptions and delays, so improving the overall flow of traffic at these intersections.

1.1 Context

The motivation behind this research is the initiative of the Municipality of Almelo towards zero-emission logistics which aims to make use of the "Talking Traffic" (*Talking Traffic* n.d.) vision, which is an innovative collaboration on the field of Smart Mobility between the Dutch Ministry of Infrastructure and Water Management, 60 regional and local authorities, but also national & international private companies. University of Twente as a public partner of "Talking Traffic" is involved in a project financed by the Province of Overijssel for the city of Almelo.

The high volumes of freight traffic in the ring road of the city and the connection with A35 have a detrimental effect in the traffic congestion at most of the intersections as these heavy-duty vehicles require more time and headway to perform maneuvers than cars. The large number of traffic lights is a big issue for the municipality and the industrial organizations in Almelo due to the delays and stops these large vehicles have to experience, which is inefficient in terms of time and monetary cost, but also environmental aspect, because they cause a lot of inefficient energy spending and carbon greenhouse gas emissions. For each stop at a traffic light, a truck is estimated to incur an extra cost of about 1 € (*Talking Traffic, TINA-4* n.d.).

1.2 Study Area

The focus of the study will be the analysis of freight traffic prioritization strategies in only two consecutive controlled intersections (area inside the red circle in Fig. 1.1), given the complexity of the problem and the limited amount of time (10 weeks) that is assigned for this project. The focal point will be one of the main junctions of the ring, intersection Weezebeeksingel - Henriette Roland Holstlaan and one intersection next to it Weezebeeksingel – Wiekslagen. The first one is the junction where most of the problems occur, due to being the main arterial road that connects the industrial area of Almelo (see Fig.1, areas noted with "IND" confined with purple) with highway A35. The direction that will be prioritized is the entry of trucks from A35 to the industrial area, direction South-East in intersection Weezebeeksingel - Henriette Roland Holstlaan, which will be the first contact with the prioritization control system and then the next intersection Weezebeeksingel – Wiekslagen. There will be a thorough analysis on the effect of introducing prioritization of freight vehicles in the traffic light and possible platooning strategies, which consist of accumulating several trucks in the queue before granting priority to multiple intersections in a row.

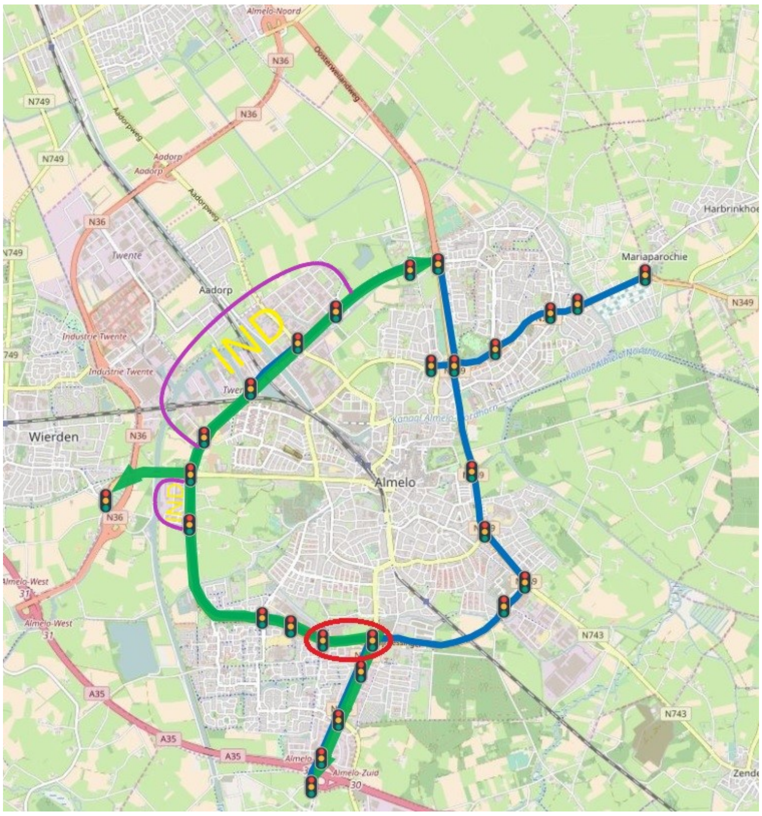

FIGURE 1.1: Study Area

1.3 Current Knowledge & Gaps

The amount of knowledge on prioritization strategies at controlled intersections is quite extensive in terms of research done in the field but is mainly focused on transit signal priority (TSP) for buses. TSP aims to reduce the delays and travel time for transit vehicles, while freight signal priority is used to reduce hard stops and red-light running (Mahmud, 2014). Freight traffic prioritization studies (Davol, 2001; Kaisar and Ardalan, 2020) have also been carried out to develop effective strategies to improve the flow of freight vehicles in urban areas. Some of them focus on developing an algorithm based on optimization functions, in which the freight vehicles' weight in the function is higher than cars, to evaluate queues in each direction and generate an optimized signal phase sequence that aims to minimize truck stops and delays at the intersection. An example of this is the pattern-based search algorithm (Zhao and Ioannou, 2016) that develops a baseline signal cycle and combines it with active priority (green extension or red truncation) when a truck approaches. The results of the simulation study showed that in both scenarios (baseline cycle generation only and combined with active priority) the network performance is improved in terms of total delay and vehicle stops with additional benefits when the truck composition of the traffic increases (Zhao and Ioannou, 2016). Active priority strategy discussed in the same research and most of the studies in the field makes use of continuous communication between trucks and traffic lights, so the drivers can request a green phase when they approach the intersection.

However, some researchers have focused their attention on a more simplified active prioritization, assuming that the trucks are autonomous such that no communication exists between vehicles and the traffic lights, but rather make use of inductive loop detectors to give the signal controller information about approaching trucks or the composition of the queue. Based on that information the traffic light algorithm changes the phase order or timings by extending a green phase, truncating the red phase or adding an extra phase to grant a green to the direction of priority in order for the targeted vehicle to pass the intersection without stopping. The results of a study using the green extension method only in an intersection with high truck density in the US concluded that it is possible to improve the travel time and reduce the number of stops of freight vehicles with little to no effect on the overall traffic at the intersection (Mahmud, 2014). However, the effects of this strategy are very limited, because priority is only granted when the phase is already running and excludes other possibilities. Furthermore, another research in a large-scale network that also deploys an active priority strategy with green extension and red truncation shows that the best-performing scenarios which improve the flow of both, trucks and cars, are those in which major roads intersect with minor roads, evenly distributed green times are assigned to each phase in the cycle and freight traffic is present mostly in major roads (Xie et al., 2022).

A study from “The Florida Department of Transportation” evaluates freight and transit priority strategies in a corridor by making use of active priority facilitated by loop detectors located 200 meters upstream of the intersection. The estimated time of the vehicle’s arrival from the moment of detection was set to 15 seconds, which means that the cycle would be adjusted such that at the estimated arrival time the light should be green by either extending a possible current green phase at that moment or shortening the other phases as much as possible to grant priority to the targeted directions at the time of arrival. The unconditional implementation of this priority in all directions resulted in lowered travel time for trucks in every direction, while for cars it was positive in the directions that are granted more priority and negative in others (Kaisar and Ardalan, 2020). However, unconditional prioritization improves the overall flow of traffic and mainly freight traffic, but it is not always possible and beneficial to provide this kind of absolute priority. In intersections in which a direction might have a much higher composition of freight vehicles than the others it can cause major uneven distribution of green time and long queues in other directions. This is the case with the Almelo case study, in which most of the traffic volume with high truck composition is coming from one direction which is the connection with the highway. The application of absolute prioritization, in this case, could lead to the mentioned consequences, so a case-specific conditional priority will be designed and evaluated for the study.

A few research projects and simulation studies have been initiated in The Netherlands mostly after 2020. Furthermore, there have also been a few locations where traffic light with target group prioritization have been tested. However, regarding the particular project, the ongoing research from University of Twente has started from 2020. There have already been conducted two research projects (Oppers, 2020;

Hal, 2021). The first one is based on a micro-simulation study performed in Vissim in the same area of interest that we are looking, which might be helpful as a starting point for the research and give some insights on possible bottlenecks that might come out. However, that study is lacking clear conclusions and important aspects of the project, such as an incomplete platooning strategy. The second research conducts a thorough analysis in the effects of prioritization in a macroscopic scale model which may not be of much relevance for the scope of our study, but it shows that there is potential for unequal benefits between prioritized and non-prioritized directions.

Our research will aim to complete the gap of knowledge in the platooning strategy and give a complete picture of the implementation of different conditional active prioritization actions in microscopic level in Almelo ring road when combined with a platooning concept of accumulating trucks in the queue to reduce the number of priority actions and disturbing other directions. Furthermore, communication between traffic controllers of the two intersections will be developed to explore the possible benefits of a more advanced methodology.

1.4 Problem Statement & Research Objective

1.4.1 Problem Statement

Freight transport in urban areas causes many problems in traffic flow dynamics and impacts the overall performance of the traffic network in the ring road of Almelo, where the industrial area is located. The large number of intersections cause a lot of delays and stops for heavy-duty vehicles and effective measures have not yet been taken to accommodate this issue.

1.4.2 Research Objective

The aim of this research is to develop freight traffic prioritization strategies and evaluate their effectiveness in terms of travel time and number of stops reduction upon implementation at two synchronized signalized intersections in Almelo ring road.

1.5 Scope

The research will be aimed to perform a microscopic scale study in only two consecutive intersections in a main node of the Almelo Ring Road nearby the connection with A35 (first one shown in Fig. 1.2 and second in Fig. 1.3). This choice is made due to the limited amount of time (10 weeks) assigned to the study. Studying two consecutive intersections might provide a better assessment of the efficacy, because in the first one the prioritization just starts and the effectiveness will be more visible in the second one. The study will be based on a microscopic simulation in PTV Vissim, which makes use of a car-following model (*Vissim* n.d.). A micro-simulation study is a great tool to assess the performance of a small traffic network by performing experiments through varying different parameters and applying strategies without disturbing the real world and in a time and cost-efficient way. This software is very advanced in modeling drivers' behavior, which would require a lot more time than is available for this study. Therefore, many aspects related to this matter will be neglected.

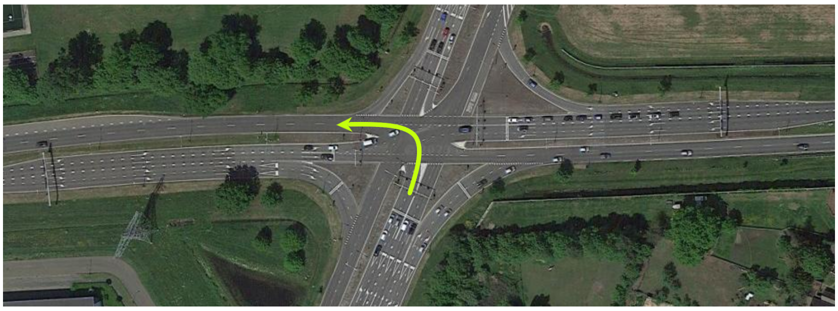

FIGURE 1.2: Weezebeeksingel - Henriette Roland Holstlaan

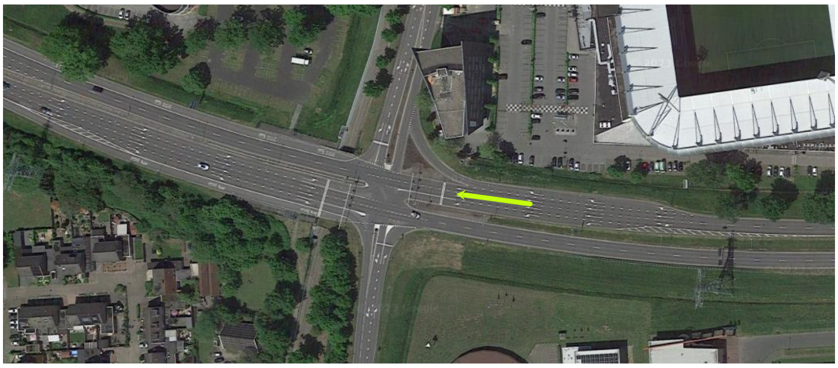

FIGURE 1.3: Intersection Weezebeeksingel – Wiekslagen

1.6 Research Questions

The research questions and sub-questions that will be answered in this study are listed below:

- How to design the conditional prioritization of freight vehicles at the signalized intersections?

  Constructing a strategy for the prioritization of the freight vehicles at the traffic light is the base of this study. To be able to answer the main question, these two sub-questions need to be answered first:

  - What are the (conditional) prioritization interventions for freight vehicles at urban intersections?
  - What is a viable platooning (convoying) strategy by making use of signal adaptation and coordination excluding vehicle synchronization?

- What is the effect of prioritizing freight traffic through signal control on travel times and number of stops?

  The assessment of the strategy will determine if it fits its purpose and achieves the objective of the research.

  - How do the travel times of freight and all mixed traffic respond to the application of these prioritization strategies in different scenarios?

  - How are the average number of stops per vehicle of the prioritized route and the intersection as a whole affected by each intervention?

Chapter 2

Methodology

The methods that will be used to conduct the research and provide answers to the research questions in the previous chapter are discussed in detail in this chapter.

2.1 Literature Research

First of all, answering the first research question on constructing an efficient strategy to prioritize the freight vehicles to improve the overall state of the traffic in the intersection, including the flow of the cars, requires a thorough literature research on freight traffic prioritization at signalized intersections. The strategy that will be studied is the autonomous intersection management (AIM), which aims to maximize the green time when a freight vehicle approaches the intersection (Xie et al., 2022). There are several strategies to grant priority, such as "Green Extension", which extends the green time or "Early Green", which truncates the red time for the direction in which a targeted vehicle is headed (Mahmud, 2014), see Fig. 2.1 for schematization of the mentioned actions. However, for these two actions to be executed it requires the priority phase to be either currently active in case of green extension or the following in case of red truncation. In case that there is another phase in between the running and the priority ones, a phase insertion which consists of adding an extra phase of prioritized direction immediately after the active one (see Fig. 2.2, the arrow indicates the trajectory of the approaching truck) is another common priority action, even though it complicates the cycle recovery more than the other two (Davol, 2001).

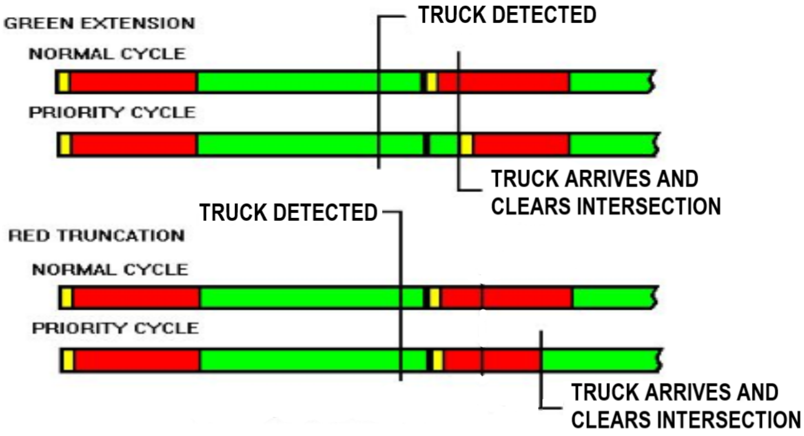

FIGURE 2.1: Green extension & Red truncation

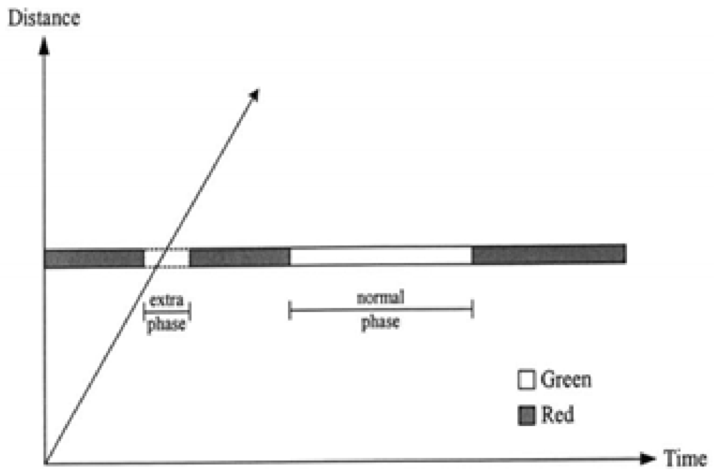

FIGURE 2.2: Phase Insertion

The freight transport makes up for a high percentage of the vehicle composition mix in the study area and giving priority by modifying the traffic lights cycle for each truck that approaches the intersection would not be the ideal situation, because it could cause a lot of delays on the other directions due to assigning most of the green time to the prioritized direction. However, a possible solution to this issue could be creating a platoon by not granting the first truck arriving immediate priority with the intention of accumulating more trucks in the queue before starting a green wave (green signal to a few intersections in a row). This strategy could imply a loss of time due to elongated red signal for the first truck that arrives until enough of them are in the queue to start a green phase. Considering this fact, there would be a tradeoff between the cost of lost time at the first intersection and the cost savings due to the platoon prioritization in the next intersections (Elbert and Knigge, 2017).

For the study, autonomous vehicles are considered which means that there is no communication between trucks about their location and no automated driving platoons as that is out of the scope of our case study in the current situation. The state of knowledge in this particular concept without active communication with the vehicles is quite limited. Therefore, experimenting with delaying the green wave priority in different scenarios and evaluating the consequences might be useful for the construction of the platooning rule.

2.2 Priority Model

The successful implementation of the active priority strategy requires the use of a loop detector upstream the traffic light. Therefore, an optimal distance to predict an approximate arrival time of the detected vehicle to the stop line and provide the traffic controller enough time to make the changes in the cycle, but also be close enough to lower the chances of the detected vehicle to change lane after the detection is determined to be 100 m upstream (Davol, 2001). Considering this distance and a posted speed limit of 70 km/h, a lower average speed of 60 km/h is used for the trucks to calculate a travel time of 6 sec from the loop detector to the stop bar under free flow conditions. However, a 3 sec slack time is added to this time to account for possible disruptions, so a 9 sec travel window should be allowed for the priority request (Chowdhury, Park, and Gingerich, 2022).

The green extension action explained in the previous section will be triggered when a truck is detected at the loop detector and the prioritized direction phase is currently running, but it is expected to be finished in the 9 seconds travel window in which the truck is expected to reach the stop line from the moment of detection. In this case, the green time will be extended such that it will hold for at least 9 seconds from the moment of detection unless the maximum green time for the phase has been reached.

A priority request when the preceding phase of the priority stage is currently running will be accommodated using the red truncation action by ending that phase early and switching to the next one which will prioritize the targeted direction as soon as the minimum green time of the preceding stage has been reached. The cycle after the priority stage continues as normal without changing the order.

Phase insertion action will be called when there is one or more phases between the active and the priority stages. In case a truck is detected and as soon as the minimum green time for the current stage has been reached, an additional priority phase of 9 seconds green time will be inserted and started immediately after stopping the active one. After ending the priority action, the phase that was due next when the priority action was called will be started.

An overview of the priority actions, how they are called and the flow of decisions is shown in the flowchart in Fig. 2.3.

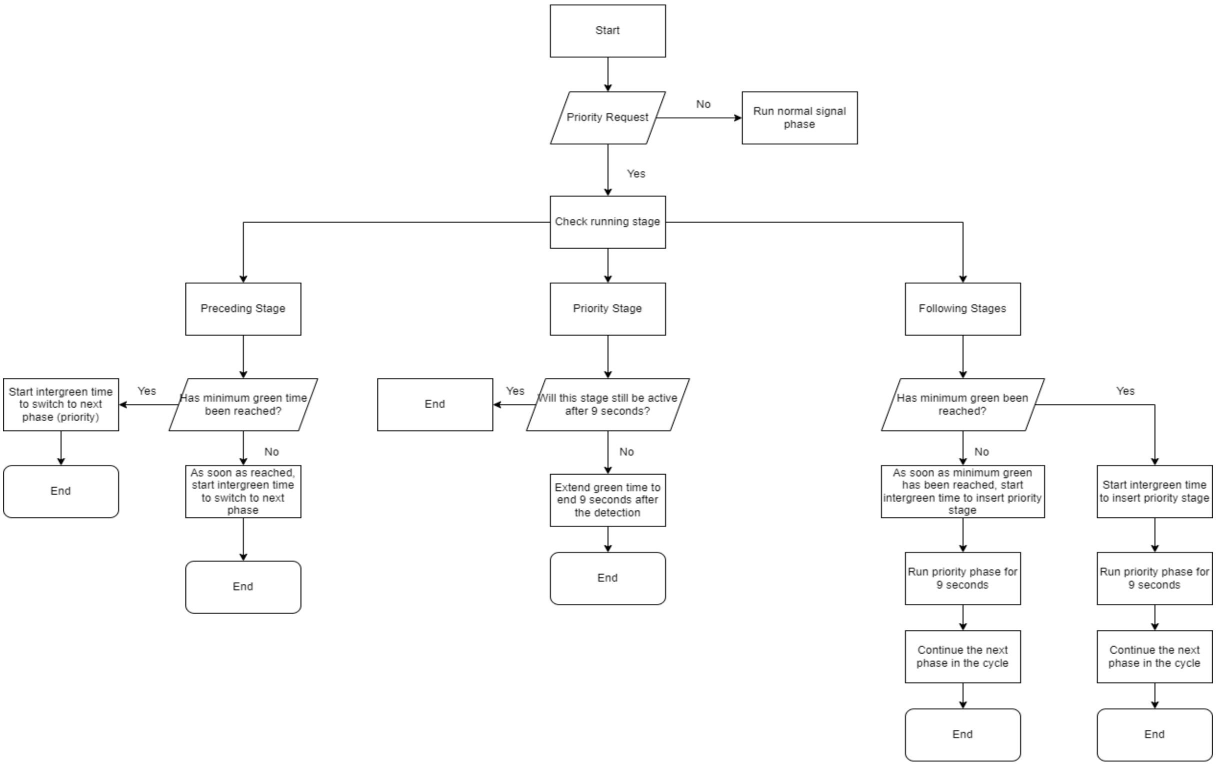

FIGURE 2.3: Priority Flowchart

2.3 Simulation

The use of a simulation software is of great importance to this study, because it provides us with an easy and effective way to perform experiments by varying different parameters and evaluating the performance of the traffic system, providing answers to the second research question. Given that we are interested in the microscopic effects of the interventions on a small scale and analyzing the performance of the intersection in terms of microscopic indicators, the use of a micro-simulation software seems to be the most appropriate. Therefore, PTV Vissim is chosen as a very advanced and effective software with multiple tools for implementation of traffic solutions and performance evaluation of the system. Vissim uses Wiedemann car-following model to model the behavior of the traffic flow based on driver's psychologic parameters. Furthermore, it incorporates many other models such as traffic controllers and lane-changing, which can be accessed to design experiments and evaluate the traffic performance by means of measurement tools (*Vissim* n.d.). A base scenario which will represent the current situation will first need to be developed. It is very difficult to find the current traffic light scheme for these intersections, therefore it is assumed that it consists of an actuated traffic light control program with minimal and maximum green times for each phase and detectors for checking if there is demand on each lane. This baseline control scenario is explained more in detail in Section 3.2.1 and will be the basis for the evaluation of the effectiveness of prioritization scenarios, in which the developed strategies will be implemented and their effect on the system will be analyzed.

A simple visualization of the implementation of prioritization in Vissim is shown in Fig. 2.4. A loop detector will provide the traffic light with information about the composition of the queue, so it will be known to the controller system when one or more trucks are detected by the loop. An optimal distance of the loop detector from the traffic light will be used together with the measured speed of the truck to be able to determine the approximate arrival time of the vehicle to the stop sign, such that in case priority will be granted, the phases of the traffic controller will be updated properly. Based on this arrival time prediction, if the phase at arrival is expected to be green for the direction that we are interested, no changes will be made to the cycle. However, if the expected phase is red, there will be either a green extension or red truncation in order to guarantee a green pass. A few scenarios will be evaluated in terms of average travel time and number of stops for specific directions and the intersection as a whole by experimenting with the platooning strategy. First, we will assess the impacts of granting priority to each truck approaching the prioritization route, see Section 3.2.2 and then implement the platooning strategy in different scenarios by delaying the green wave until two or more trucks are present in the queue, unless the green phase of the normal cycle starts without modifying the sequence, see Section 3.2.4. Furthermore, the simulations will be run for two demand scenarios: peak (7AM-9AM & 4PM-6PM) and off-peak , because it will provide us with the impact and efficiency in each situation to be able to give specific recommendations for the implementation of proposed strategies, see Section 3.4. For the peak demand, real turning volumes data measured at the intersection (see Appendix A) is supplied to the simulation. Off-peak volume input is represented by downscaling the peak data with a factor, see section 3.4.

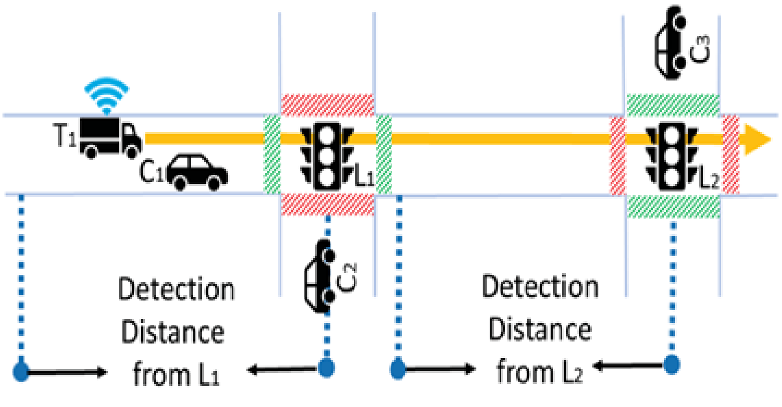

FIGURE 2.4: Prioritization illustration

Chapter 3

Model Development

The construction of a base model that represents the current conditions of the traffic network in the study area is carried out in Vissim, which will be used to test the proposed interventions. The model consists of two consecutive intersections only. Intersection Weezebeeksingel - Henriette Roland Holstlaan is represented in the model as in Fig. 3.1 and intersection Weezebeeksingel – Wiekslagen is shown in Fig. 3.2. The proper number of lanes and road geometry is modelled for each section of the road according to Google Maps. Furthermore, the signal heads at the end of each lane entering the intersection are used as in the real current situation.

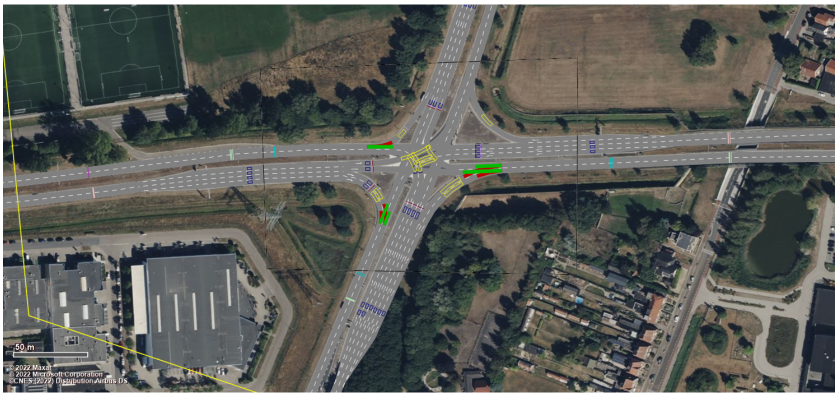

FIGURE 3.1: Weezebeeksingel - H. R. Holstlaan (K1) Model

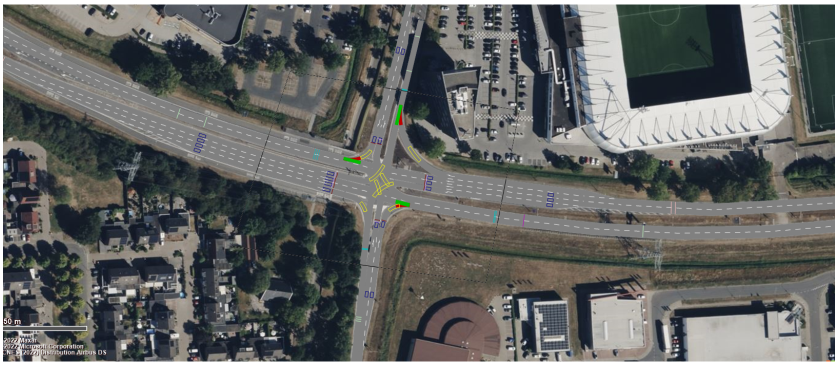

FIGURE 3.2: Intersection Weezebeeksingel – Wiekslagen (K2) Model

3.1 Data Input

The simulation needs to be fed a lot of data that are secured from different sources. Necessary data include vehicle counts and traffic composition in the area of interest. Traffic count data are provided by the research department of Civil Engineering and Management of University of Twente. Furthermore, data from recent studies in the same area such as "Talking traffic on Almelo Ring Road" (Oppers, 2020), are useful. The simulation software allows access to drivers' behavior parameters, but it will not be considered for the scope and time limitation of this research, so Vissim's default car following parameters will be used.

The turning volumes of morning peak hours (*Telcijfers VRI's Almelo* 2017) registered in the intersections are used to supply the model and are scaled to represent different traffic saturation scenarios. For the peak scenario, the demand from the data in Appendix A has been used, while for the off-peak, this demand is reduced by 30 %, see Section 3.4. The vehicle composition of the traffic is also a very important input variable for the model development. The 24-hours percentages of freight traffic measured in the studied intersections for different directions are supplied to the simulation (*Actualisatie RVM Twente* 2016). However it is varied during the simulation of different scenarios as the percentage of heavy vehicles during normal hours are higher than peak hours, so the traffic composition changes throughout the day, see Section 3.4.

3.2 Signal Control & Priority Scenarios

Signal control is the main object of this study as it is used to implement the proposed priority interventions. A baseline signal control to represent the current situation and the configurations of the signal control for each priority strategy are described in this section.

3.2.1 Baseline signal control

The signal controllers for the main and the secondary intersections are programmed using a vehicle-actuated programming language, an extension of Vissim called VisVap, which makes use of control algorithms to provide the simulation with an actuated traffic light controller. The base scenario that aims to represent the current control program at both intersections is an actuated control facilitated by detectors in each lane to provide the controller with information about the demand for each stage, so that green will be given only to directions which have cars waiting. If a stage is active and the queue is cleared, the controller switches to the next stage which has demand after the minimum green time for the active stage has been reached. Otherwise, if there are still vehicles approaching to pass on the lanes which are given green on the active stage, it will continue to run until the maximum green time for that stage has been reached. The stages used, the minimum and maximum green times for each stage and intersection based on the turning volumes are described in Appendix B. The actuated control logic in VisVap for the base scenario is the same for both intersection and is shown in Fig. B.3 in Appendix B.

3.2.2 Absolute priority scenario

Absolute priority will be tested for the prioritization route, direction South-West in the main intersection Weezebeeksingel – H. R. Holstlaan. The priority stage corresponds to stage 3 in the controller cycle of this intersection shown in Appendix B . In case a truck is detected in one of the detectors upstream the two left-turn lanes (Fig. 3.3), which correspond to the priority route, one of the priority actions explained in Section 2.2 will be triggered. If stage 3 is already active when a freight vehicle is detected, it will only be extended to allow time for the truck to pass. If another stage is active and minimum green time for that stage has been reached, either red truncation or phase insertion actions will be called to grant the truck immediate priority, see Appendix C for the complete control logic implemented in VisVap.

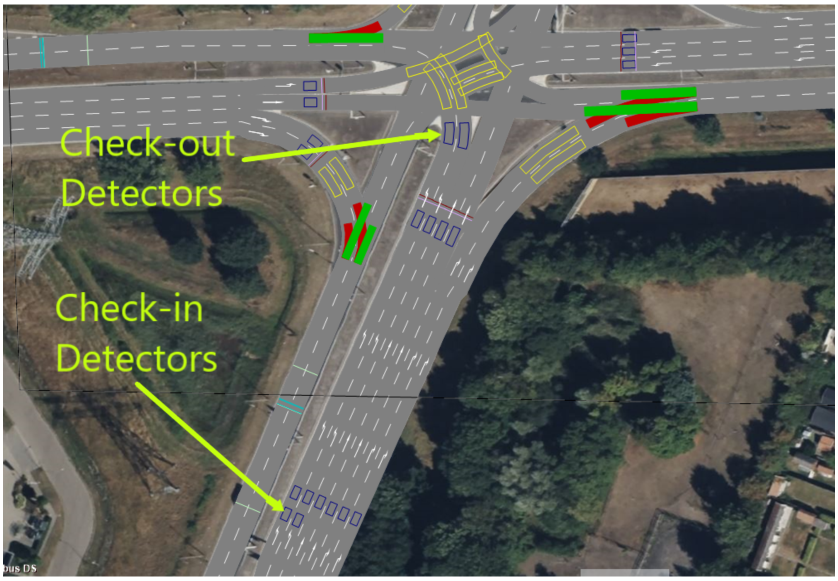

FIGURE 3.3: Weezebeeksingel - H. R. Holstlaan (K1) Model

3.2.3 Absolute priority with recovery cycle

The absolute priority with a recovery cycle tends to limit the number of priority calls and achieve a more evenly distributed green time between stages within the cycle. The priority is called in the same way as in the absolute priority scenario, so when a truck is detected upstream, but after a prioritization action is triggered, one normal cycle is run without priority even if a truck is detected, see VisVap control logic in Appendix D. This is called a recovery cycle that aims to recover the green time lost for other stages when the priority action was executed and clear potential queues accumulated on the other phases.

3.2.4 Platooning scenarios

Conditional priority is the main focus in this research. Scenarios of accumulating 3 or 4 trucks in the first intersection before granting priority and establishing communication with the next traffic controller to start a green wave will be tested. If the chosen number of trucks is accumulated in the queue for the South-West direction and the priority stage is not active, one of the priority actions mentioned before will be triggered and at the same time the next intersection will be informed that a platoon is arriving and after approximately 30 seconds, which corresponds to travel time from the first to the second intersection, stage 1 of the second controller must be active, which grants the continuation of priority for the trucks on the targeted route at this intersection in direction East-West, see control logic of the first intersection (K1) and the second intersection (K2) in Appendix E.

3.3 Key Performance Indicators (KPI's)

The performance indicators that will provide a measurement of the effectiveness of the used prioritization strategies are the average travel time to pass the intersection and the average number of stops per vehicle. The travel time is a useful performance indicator to monitor the effect of the traffic flow at the junction as it is directly related to the delays. The average number of stops is a great assessment tool for the purpose of our study as we aim to minimize the stops for freight vehicles to increase energy efficiency and emissions reduction.

The performance indicators will be measured for the traffic as a whole, but also for trucks only. The average travel time per vehicle will be measured as the average time of all travel directions to travel the same distance of 300 m, see Formula below. It is evaluated on each intersection separately to get an overview of the effects of the interventions on the performance of each junction. Furthermore, an additional travel time measurement that crosses both intersections on the freight (prioritization) route is installed from the South-West direction on the first intersection up to past the East-West direction on the second intersection with a route length of 850 m for freight vehicles only. It will provide insight on how the travel time of the trucks is affected in each scenario and answer the second research question.

$$K = \frac{\sum_{d=1}^{12} t_d * V_d}{\sum_{d=1}^{12} V_d}$$

$$K - Average\, travel\, time\, per\, vehicle\, for\, the\, whole\, intersection$$

$$t_d - Average\, travel\, time\, for\, direction\, d$$

$$V_d - Number\, of\, vehicles\, for\, direction\, d$$

The number of stops will be measured from queue counters in each lane at both intersections. A stop is considered when the speed of a vehicle drops below 5 km/h. The sum of the number of stops of all directions divided by the total number of vehicles that cross will be the average number of stops per vehicle for each intersection as the second performance indicator that shows the effects of the proposed solutions on this KPI. Additionally, the average stops are counted for the priority route only, so the sum of the stops in South-West queue counter in Weezebeeksingel – H. R. Holstlaan and East-West queue counter in Weezebeeksingel – Wiekslagen, divided by the number of vehicles that follow this route on both intersections. This indicator will provide an answer to the second sub-question of the second research question.

3.4 Experimental set-up

The simulations have been run for periods of one hour, preceded by 5 minutes of warm-up time, which is enough to load up the network. They are run for the base control and each priority scenario, for peak and off-peak demand. The peak and off-peak demand with hourly turning volumes used for each scenario are shown in Table 3.1. Furthermore, the traffic composition during these two scenarios is also different, see Table 3.2.

	K1		**K2**	
	Peak	**Off-Peak**	**Peak**	**Off-Peak**
ES	639	447	98	69
EN	35	25	9	6
EW	290	203	710	497
WN	90	63	9	6
WE	184	129	719	503
WS	325	228	90	63
SE	548	384	173	121
SN	673	471	9	6
SW	549	384	52	36
NW	113	79	22	15
NS	492	344	22	15
NE	42	29	22	15

TABLE 3.1: Turning hourly volumes supplied to the simulation

	Peak		**Off Peak**	
	K1	K2	K1	K2
South	15 %	12 %	20 %	18 %
East	12 %	12 %	18 %	18 %
West	12 %	12 %	18 %	18 %
North	12 %	12 %	18 %	18 %

TABLE 3.2: Freight traffic composition per direction

The outputs of the simulations that are collected include: vehicle travel times for each origin-destination pair for both intersections and queue results that provide the number of stops at each queue that is formed at any controller stop line. Furthermore, a vehicle travel time measurement is defined to measure the time that the trucks take to cross both intersections on the priority route. All these results are then analyzed in the Excel file attached to the report to provide the key performance indicators that are defined in Section 3.3. As a stochastic process, each scenario needs to be replicated multiple times to achieve statistically significant results at an accuracy of 95 %. Initially, 5 simulations are run for each scenario to determine how many more are needed to achieve the level of significance defined based on the Formula below. The priority route travel time of trucks is chosen as the KPI to determine the number of simulations needed as the KPI with most variation. For the off-peak simulations, 5 replications were enough for each priority scenario to achieve results with a significance level of 95 %, while for the peak scenarios more were needed due to higher variability. 10 replications were then run for the peak scenarios and tested more than enough to be statistically significant to our requirements.

$$R = (\frac{t_{a/2} * S}{X * r})^2$$

$$t_{a/2} - Critical\ value\ of\ t - distribution$$

S - Standard deviation of KPI

X - Average of KPI's for the simulations that are run

r - Relative error allowed (5%)

Chapter 4

Results

The tracked results of the key performance indicators of the simulation experiments explained in the previous section chapter are described below. These results will provide answers to the research questions and assess the effectiveness of the proposed priority strategies.

4.1 Average travel time

The results of average travel time (seconds) per vehicle for intersection Weezebeeksingel – H. R. Holstlaan (K1), intersection Weezebeeksingel – Wiekslagen (K2) and for the freight route that crosses both intersections will be evaluated and discussed in this section for each priority and demand scenario.

4.1.1 Peak

The average travel time results for the peak scenario are shown in Table 4.1. The absolute priority in the first intersection leads to a sharp increase of 18% in the average travel time of the whole junction. The recovery strategy limits the prioritization of trucks, so there is a 3 seconds increase in their travel time in the objective route compared to absolute priority, but the impact on the whole junction is reduced substantially compared to it. The best performance on lowering the journey time of freight vehicles on the priority route is achieved in the 3-trucks platoon scenario with a decrease of 23% for this route and 1% on the whole K2, but a small increase of 2% on first intersection travel time from the base scenario, see Fig. 4.1 for percentage changes of the performance indicator of each priority strategy from the base scenario.

This decrease of trucks' travel time in the 3-trucks platoon scenario shows that the coordination with the following traffic controllers lowers the impact on the whole first junction while improving the travel time for the prioritized vehicles even more than absolute priority that prioritizes every truck in the first intersection but lacks communication with the following ones, which also causes huge delays to the other directions in the junction due to unlimited priority calls and cycle changes. The reason behind this is that the priority actions in the first intersection are limited as it takes some time until three trucks are accumulated in the queue, so some time is lost in the first junction, but it is compensated in the second one due to the green wave which grants the platoon direct priority.

	Base	Absolute	Recovery	Platoon-3	Platoon-4
K1	44.8	52.8	45.9	45.7	45.2
K2	27.5	27.2	26.7	27.2	28.0
Freight	100.4	78.5	81.3	77.5	87.3

TABLE 4.1: Peak average travel time per vehicle (seconds)

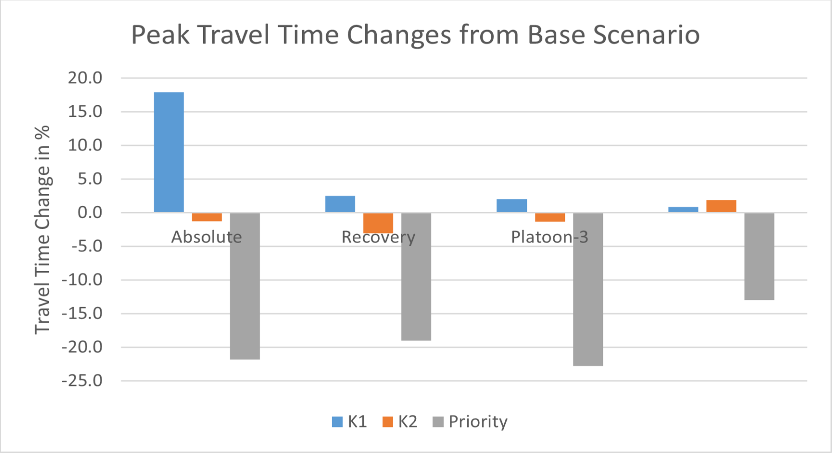

FIGURE 4.1: Percentage average travel time change compared base scenario in the peak period

4.1.2 Off-Peak

The results of average travel time for the off-peak simulations are shown in Table 4.2 and the percentage changes from the base scenario in Fig. 4.2. The absolute priority achieves the best freight route travel time but at the cost of a 3.5 % increase in the average travel time of K1, which is the largest of all scenarios. The recovery strategy lowers the freight travel time measurement by 14 % and the second intersection average travel time by 2%, while causing a 2% increase in the first one, which is a lower worsening of K1 performance than the absolute and platoon-3 scenarios while achieving similar results on the freight travel time. The 4-trucks platoon scenario has the lowest effect on K1, but the benefits for the trucks' priority are very limited compared to the other interventions.

The consequences of different interventions on K1 and K2 are different compared to the peak scenario. The negative effect of absolute priority on K1 travel time is lowered from 18% (peak) to 3.5% (off-peak). The performance of absolute priority and recovery strategy show an improvement compared to the peak scenario.

	Base	Absolute	Recovery	Platoon-3	Platoon-4
K1	37.0	38.3	37.9	38.1	37.2
K2	24.3	24.5	23.8	24.9	24.9
Freight	84.8	72.2	73.1	72.7	77.7

TABLE 4.2: Off-peak average travel time per vehicle (seconds)

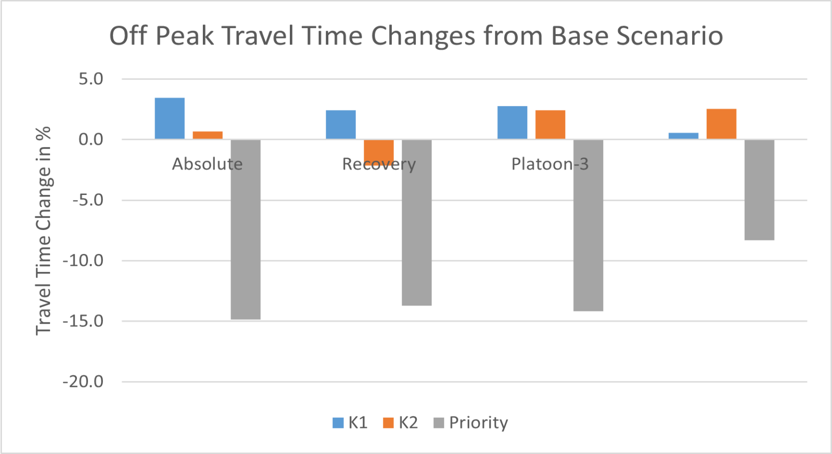

FIGURE 4.2: Percentage average travel time change compared to base scenario in the off-peak period

4.2 Average number of stops

The results of the average number of stops (stops/vehicle) for intersection Weezebeeksingel – H. R. Holstlaan (K1), intersection Weezebeeksingel – Wiekslagen (K2) and for the freight route that crosses both intersections will be evaluated and discussed in this section for each priority and demand scenario.

4.2.1 Peak

The results of average number of stops per vehicle during peak simulations are shown in Table 4.3 and the percentage deviation of each scenario from the base in Fig. 4.3. As can be seen, the absolute priority intervention yields the lowest freight route average stops when crossing both intersections but increases the stops for K1 by 2%. On the other hand, recovery and 3-trucks platoon scenarios lower the priority stops by 27% and 29% respectively, while also reducing the overall stops for the whole intersection K1 and K2, which is an ideal case. The effect of 4-trucks platoon in the priority route is quite limited compared to the other interventions.

The reason behind the recovery and platoon-3 scenario lowering the number of stops of the whole junction K1 might be the balance of green time distribution between phases and assigning more green time to phase 3 (priority) which corresponds to the Southbound approach, where most of the traffic volume is coming and consequently stops in this road stretch are reduced significantly. It is the same case for K2, in which the East-West direction is the busiest, and again it corresponds to the priority route.

	Base	**Absolute**	**Recovery**	**Platoon-3**	**Platoon-4**
K1	1.06	1.08	0.99	1.01	1.08
K2	0.67	0.64	0.60	0.63	0.65
Freight	3.56	2.47	2.57	2.53	3.28

TABLE 4.3: Peak average number of stops per vehicle

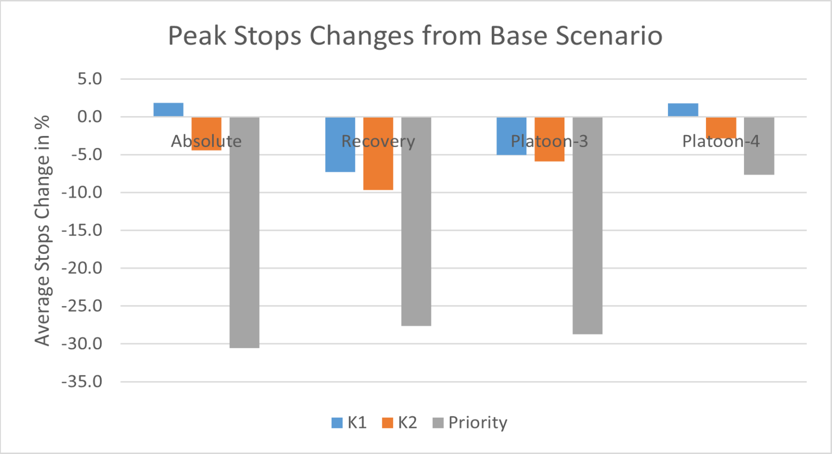

FIGURE 4.3: Percentage average number of stops change compared to base scenario in the peak period

4.2.2 Off-Peak

The average number of stops results during off-peak demand conditions differ from the peak situation, see Table 4.4 and Fig. 4.4. Absolute prioritization lowers the freight route stops by 18.5 % and the K1 overall stops by 6%, while increasing the K2 stops by 3.5%. The recovery strategy achieves the same decrease for the freight route as the absolute, but at the same time lowers the stops of both, K1 and K2. 3-trucks and 4-trucks platoon scenarios yield similar results by decreasing the average stops of the objective route at a lower rate than the previous two scenarios, but increasing the stops of K1 and K2. Similarly to the results of the travel time during off-peak period, the recovery scenario performs better under unsaturated conditions than the platoon ones.

	Base	**Absolute**	**Recovery**	**Platoon-3**	**Platoon-4**
K1	0.73	0.69	0.71	0.74	0.74
K2	0.44	0.46	0.43	0.46	0.46
Freight	2.16	1.76	1.76	1.93	2.09

TABLE 4.4: Off-peak average number of stops per vehicle

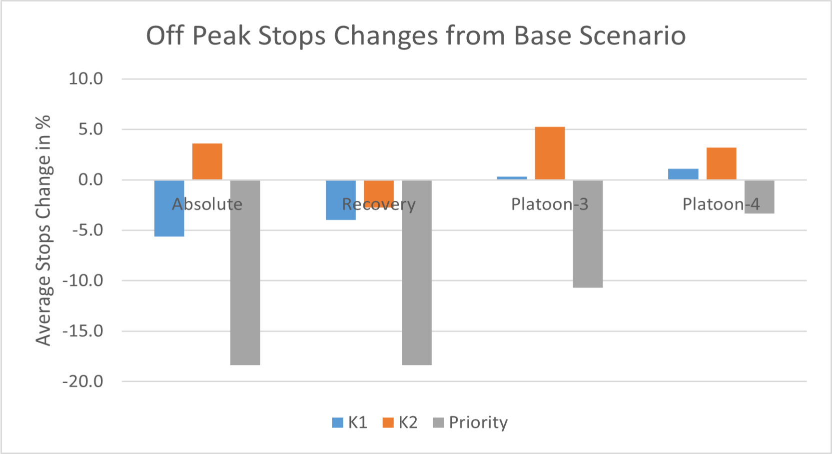

FIGURE 4.4: Percentage average number of stops change compared to base scenario in the off-peak period

4.3 Directional travel time

The results of average travel time for each direction of K1 (ES, EN, EW, WN, WE, WS, SE, SN, SW, NW, NS, NE), freight (priority) route, and K2 (2EW, 2WE, 2WN, 2WS, 2SN, 2ES, 2NS) are discussed in this section.

4.3.1 Peak

The directional travel time of each priority intervention in the peak period are shown in Fig. 4.5. The directional travel time changes in seconds compared to the base scenario are represented in Fig. 4.6. As can be seen, absolute priority causes a sharp increase in directions other than the prioritized ones in K1, but has almost no effect on K2, because all the actions are taken in K1 and no communication with K2 exists in this scenario. The large effect on other directions of K1 is caused by intervening with the cycle a lot and assigning most of the green time to the prioritized phase. The recovery scenario worsens the travel time in the eastbound approach of K1, but has more or less the same effect on the other directions except for prioritized ones as the base scenario. The 3-trucks platoon scenario causes a slight increase in the West-East and North-South directions of K1 and WN, SN, and NS directions of K2, but all other directions except for priority show no significant change.

The increase in K2 during platooning scenarios is caused due to the coordination with K1, because every time that phase 3 of K1 that corresponds to the priority route is active, a signal is sent to K2 so that its phase 1 that prioritizes East-West should be active after approximately 30 seconds to ensure a green wave. This causes many changes in the cycle order of K2 and directions with very few traffic volumes such as 2SN and 2NS are impacted the most in this case.

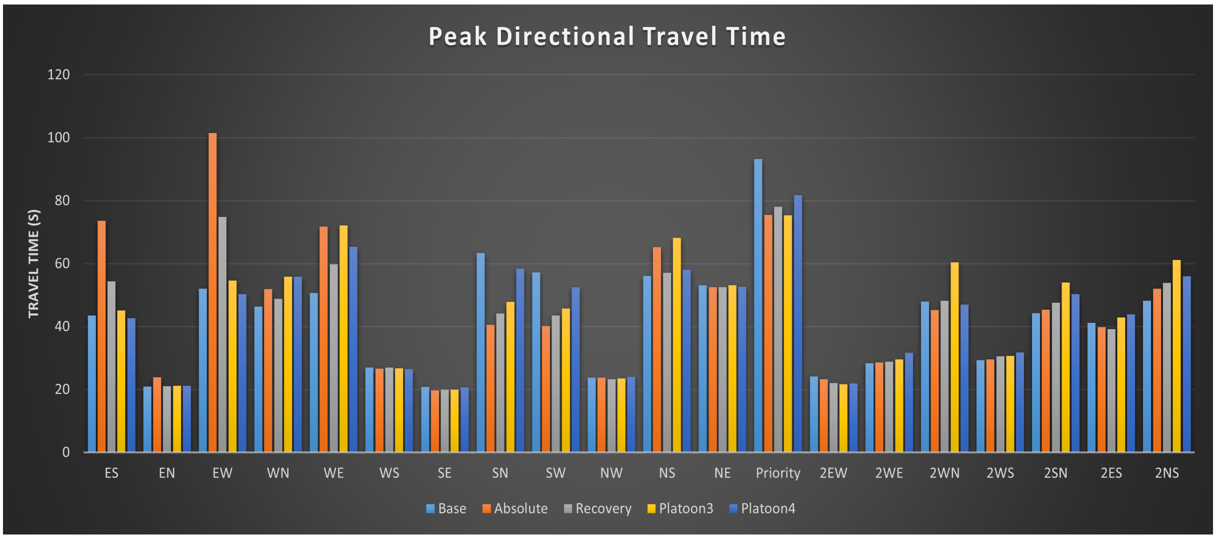

FIGURE 4.5: Directional travel time in the peak period

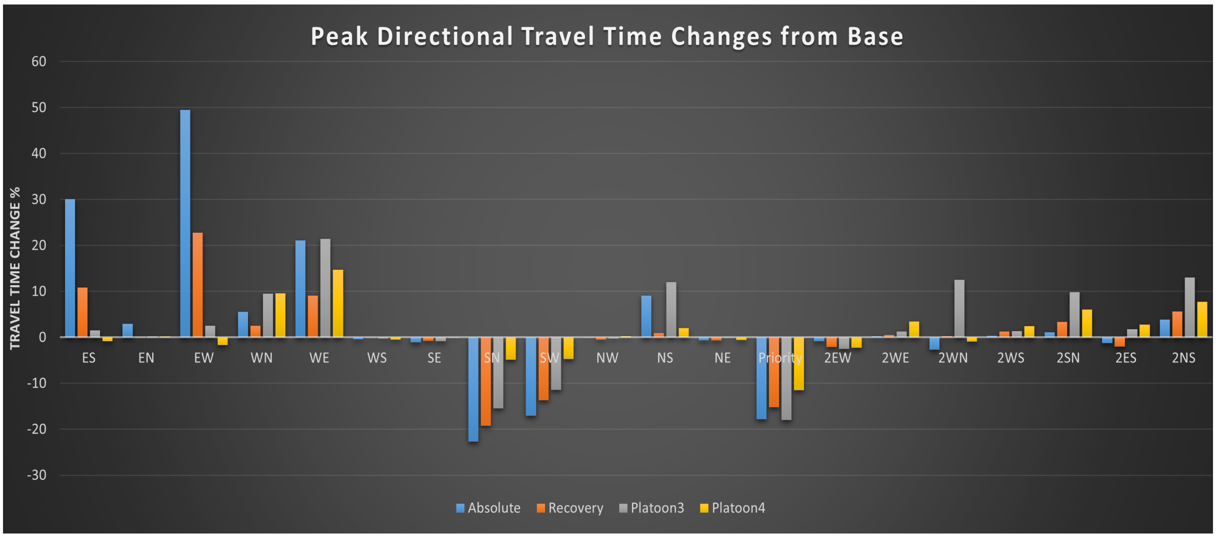

FIGURE 4.6: Directional travel time change compared to base scenario in the peak period

4.3.2 Off-Peak

The directional average travel times during off-peak demand are shown in Fig. 4.7 and changes in travel time in seconds for each priority scenario from the base are demonstrated in Fig. 4.8. Absolute prioritization leads to the highest consequences on other directions of K1, but no effect on K2 as it is expected. The recovery scenario yields an increase in the Eastbound approach of K1, but little to no effect on other directions of K1 and K2 except the prioritized. 3 and 4-truck platoon scenarios cause a worsening of travel time in the westbound approach of K1 and almost all other directions of K2 other than the prioritized ones. In general the directional effects on travel time are similar to the peak scenario, but lower in magnitude.

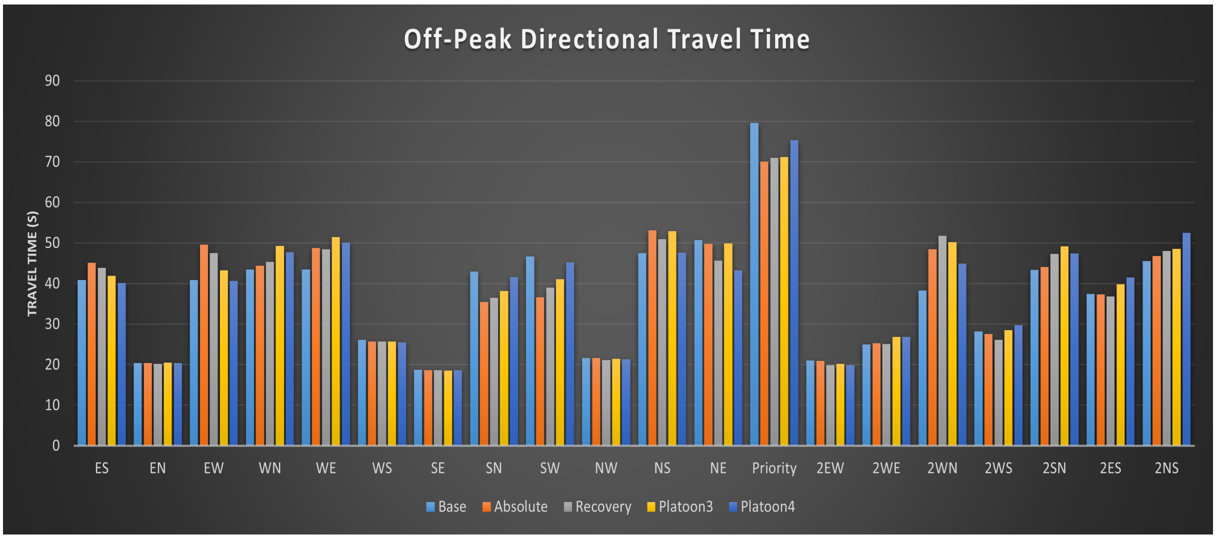

FIGURE 4.7: Directional travel time in the off-peak period

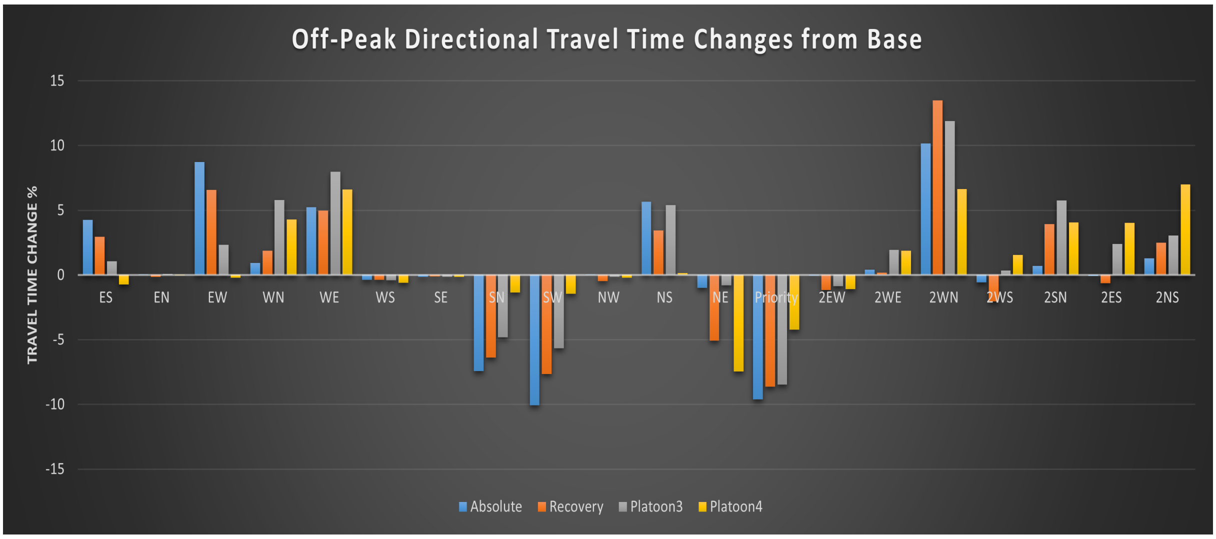

FIGURE 4.8: Directional travel time change compared to base scenario in the off-peak period

4.4 Travel time variation of trucks on the freight route within peak scenario

The variation of travel time of trucks on the priority route within a simulation run is important to get a picture of how are the averages that we observed before obtained (is there a regularity in the travel times or are there some vehicles with very low and some with very high travel times that compensate each-other?). In Fig. 4.9, the box plots (statistical tool to represent the spread of a dataset) of travel time data for base, absolute and platoon scenarios during peak period are depicted. As can be seen, the travel time of trucks during base scenario is very irregular as the travel times vary from around 50 s to 175 s with an average of 100 s. On the other hand, the absolute and platoon scenarios show a very regular travel time behavior with a small spread between 50 s and 100 s. This means that the reliability of the travel time of trucks during peak hours is higher when priority interventions are implemented and that averages are more meaningful.

FIGURE 4.9: Box plot for individual travel time of trucks on the freight route for each priority strategy (peak period)

Chapter 5

Discussion

The design process and the credibility of the results is discussed in detail in this section to be able to give valuable advice on the implementation of the proposed interventions. First and foremost, the use of a microsimulation software tends to imitate the behavior of the real traffic system, but always presents limitations compared to on-site experiments, as many assumptions are made by generalizing drivers' behavior and idealizing the traffic system. However, it is a credible and time-efficient tool to assess the effects of different interventions in a traffic network. Additionally, the data input used for the simulation is retrieved from old volume measurements in the actual intersections, so the peak volumes might be even higher in the current situation in the study area.

Secondly, the proposed conditional (platooning) intervention is only prioritizing one direction by making use of loop detectors upstream (check-in) and downstream (check-out) to give the control system information about the number of trucks waiting in the queue of the prioritized direction. However, it happens that a truck crosses the check-in detector and then changes lane to another turning direction, so it does not check-out in the direction that it checked-in. In this case the controller receives the wrong information about the number of the trucks in the queue for that direction. This phenomenon happens in the simulation, but it might happen in the real world as well, so it is an advantage that the model is not perfect in determining the queue composition. To overcome this discrepancy in the simulation, it is assumed that after every green phase in the priority direction, the queue is totally cleared and the truck count starts from 0, after the green time is finished. However, this might not always be the case in the real situation, mostly during peak periods.

Fixed times are defined for the changes in phases' timings to grant priority to a truck or a platoon. It assumes almost free-flow conditions, but it might happen that the vehicle takes more time than calculated to arrive at the intersection from the upstream detector. This adds more uncertainty and reduces the effectiveness of the priority strategy.

The results showed that absolute priority is not efficient in prioritizing the freight traffic in only one direction, because it causes too many disruptions in the other directions due to uneven green time distribution between stages and unlimited priority calls. Even though it sharply decreases the travel time in the direction of priority, absolute priority increased the average travel time and the number of stops of the whole intersection substantially, making it a non-optimal strategy to be implemented. The negative effect in the other directions is more noticeable during the peak period, so it seems to be directly related to the traffic volume.

Priority with recovery strategy aimed to decrease the number of priority actions and allow the controller to run a normalizing cycle. The results showed that the effects on the other directions of travel are reduced significantly compared to absolute prioritization, while still lowering the prioritized route travel time at a very high rate. This strategy showed to perform the best during off-peak period by causing an insignificant increase in the average travel time of the first intersection and decreasing the stops for both junctions while lowering the travel time and stops of the freight route substantially.

The conditional (platooning) priority strategy resulted very beneficial during peak hours. The high volume of traffic at the junctions during this period does not allow for very frequent priority actions, as the queues in the other directions accumulate fast. Therefore, waiting for a number of trucks to be accumulated before granting priority, reduces the negative effects on the whole first intersection, as the priority actions are reduced. In this case, some time is lost at the first junction, but it is clearly compensated by absolute priority at the second one each time that priority is granted to a convoy of trucks. The effect on the travel time of the first intersection is negligible. There is a little increase in the travel time of other directions (not prioritized) of the second intersection due to the communication with the first one that requests priority for a platoon and forces it to change the phase order properly, but mainly in the directions with very small volumes. Apart from this, during peak the reduction in travel time and stops for the freight route is at the same rate as absolute priority, which is quite high. Finally, the total number of stops for both junctions is reduced.

In general, the proposed conditional priority seems to improve the flow of trucks in terms of travel time and stops reduction while keeping the disturbance on the other traffic very low (almost insignificant) during peak period. These reductions play an important role in increasing the energy efficiency (reducing fuel consumption) of the trucks and decreasing gas emissions, which were the main concerns of the stakeholders of this project. However, the simplifications and idealizations of the model might have an effect on the results. Therefore, some uncertainty exists regarding the mentioned claims.

Chapter 6

Conclusion

The focus of this study was designing the conditional prioritization of freight vehicles across two consecutive intersections and evaluating their effectiveness in terms of reducing the travel time and the number of stops for these large vehicles. The result in the previous section will answer the research questions of this study:

- **What are the (conditional) prioritization interventions for freight vehicles at urban intersections?**

  Different prioritization strategies are constructed to be able to come up with the best intervention under different traffic demand and composition scenarios. Firstly, the absolute (unconditional) priority strategy that grants immediate priority to each truck approaching the intersection was considered. However, the objective of this research focuses on conditional priority, so two more intervention strategies are constructed. The priority with a recovery cycle grants priority to the objective direction when a truck is detected upstream, but after a priority action is executed, one normal cycle runs without possible priority calls. Lastly, the platooning strategy focuses on accumulating trucks in the queue, such that priority will be granted to a so-called platoon, in which multiple trucks will be moving in the same direction and start a green wave across the following intersections.

- **What is a viable platooning strategy by making use of signal adaptation and coordination excluding vehicle synchronization?**

  The platooning strategy constructed focuses on holding the grant of priority at the first intersection until a fixed number of trucks determined beforehand based on the demand is accumulated in the priority queue and then starting a green wave by communicating to the next intersection that a platoon is arriving. The controller of the next junction will manipulate the phase order such that after the approximate travel time from the previous intersection to this one, the phase that grants the continuation of the priority route should be active to avoid stopping the platoon.

- **How do the travel times of freight and all mixed traffic respond to the application of these prioritization strategies in different scenarios?**

  The absolute priority in general is the most beneficial for the travel time of freight vehicles on the priority route, but causes major disturbance to other directions of travel when it is applied due to the large and unlimited number of priority calls and cycle changes that assign most of the green time to the prioritized phase. However, a major reduction of disturbance on the whole junction is observed when the demand is lower during off-peak hours as the average travel time of the whole intersection does not increase as much as during peak demand.

The recovery strategy aimed to limit the prioritization rate reduces the negative effect on the whole travel time performance of the junction, but still achieves a very good freight route travel time reduction, even though less profitable for the trucks than the absolute priority. The lowered consequences on the whole intersection compared to the absolute scenario are most noticeable during peak hours. On the other hand, during off-peak demand, the recovery strategy seems to be the best performing by causing a minimal effect on the whole intersection but reducing the travel time at almost the same rate as absolute priority.

The platooning scenario was developed to reduce the negative effects on the performance of the whole intersection mostly during peak hours when many changes to the normal cycle cause too many disruptions. The accumulation of trucks at the first intersection implies some loss of time, which is apparently compensated in the second intersection, in which the platoon is granted immediate priority. The platoon scenario with three trucks in our case study is the best performing during peak hours in terms of travel time of the priority route with minimal effects on the whole junctions involved.

- **How are the average number of stops per vehicle of the prioritized route and the intersection as a whole affected by each intervention?**

  The absolute prioritization similarly to travel time results, also reduces drastically the number of stops for the prioritized direction but increases the average number of stops for the whole intersection due to large queues being formed in the other directions of travel.

  The recovery and 3-trucks platoon scenarios both lower the average number of stops per vehicle for both intersections during the peak demand. The reduction of freight route stops is at a high rate for both interventions again during peak but the platoon strategy performs better in terms of reducing trucks' stops. The off-peak demand scenario yields different results for the stops' KPI by reducing the stops for the freight route from the recovery scenario to the same extent as the absolute priority and at the same time reducing stops for K1 and K2. The platooning scenario's performance during off-peak is worse than the recovery one because it worsens the average stops KPI for both intersections in general.

Chapter 7

Recommendations

The recommendations for the correct use of this research are very important to pave the way for future research and possible implementation of the proposed priority strategies.

This study focused on the effect of applying the interventions only in two consecutive intersections. However, expanding the network across a corridor might produce more useful insight into the macroscopic effect of the strategies, especially the platooning strategy that involves coordination to start a green wave in one direction. In that case, the green wave along the whole corridor is far from reality as there are many complications that come up.

The demand scenarios used are limited to peak and off-peak scenarios. However, experimenting with varying the demand and traffic composition from very low to capacity might provide a better understanding of how do different performance measurements relate to the demand. It is recommended to look further into the microscopic effects of the interventions in all directions and analyze the reasons why specific directions are improved or worsened.

Finally, this study focused on prioritizing only one direction, which in this case has a high freight traffic volume and composition due to the connection of a highway with the industrial area. This is not the case for every junction as there are intersections with high truck volumes in many directions. Therefore, implementing the priority in all directions might not be as beneficial as in this case. This requires further research and evaluation.

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Appendix A

Vehicle input

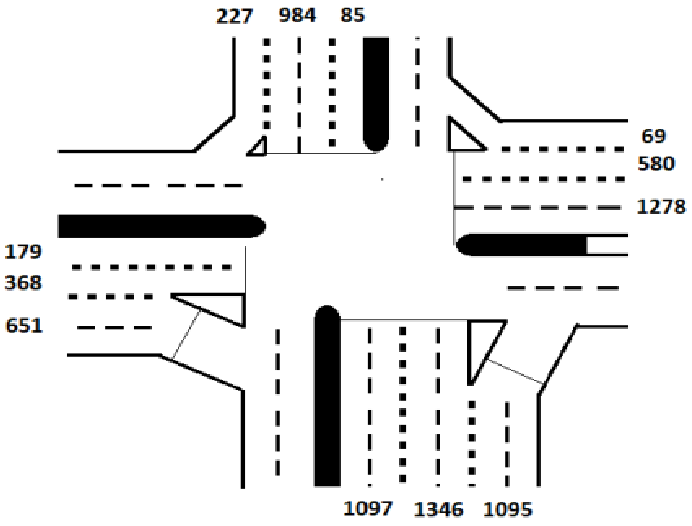


FIGURE A.1: 2-hour morning peak intensities for Weezebeeksingel - H.R. Holstlaan (*Telcijfers VRI's Almelo* 2017)

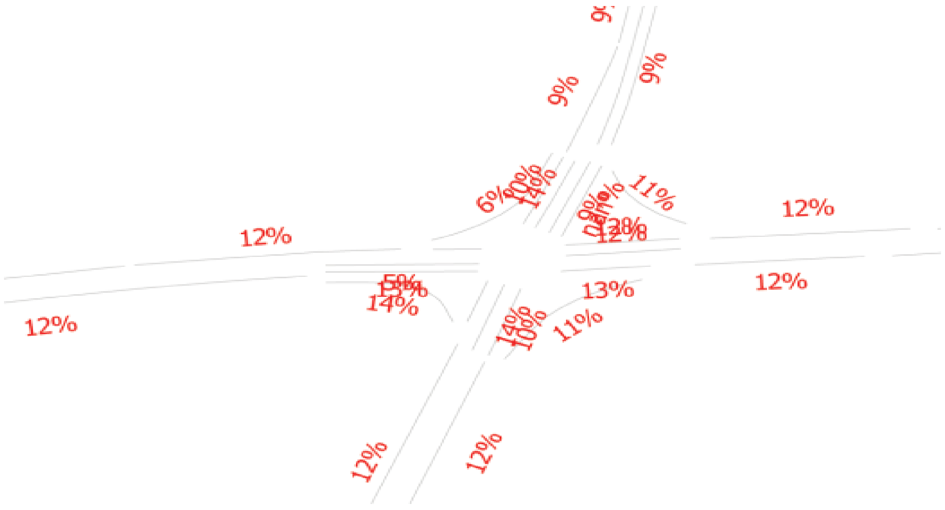


FIGURE A.2: 24-hour percentage of freight traffic for Weezebeeksingel - H.R. Holstlaan (*Actualisatie RVM Twente* 2016)

Appendix B

Baseline signal control

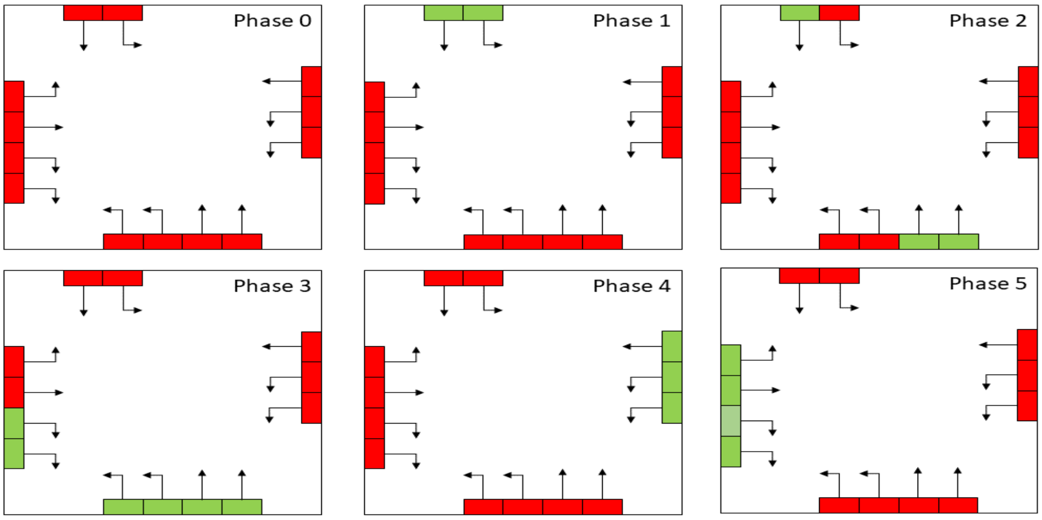


FIGURE B.1: Phase diagram intersection Weezebeeksingel - H. R. Holstlaan (K1)

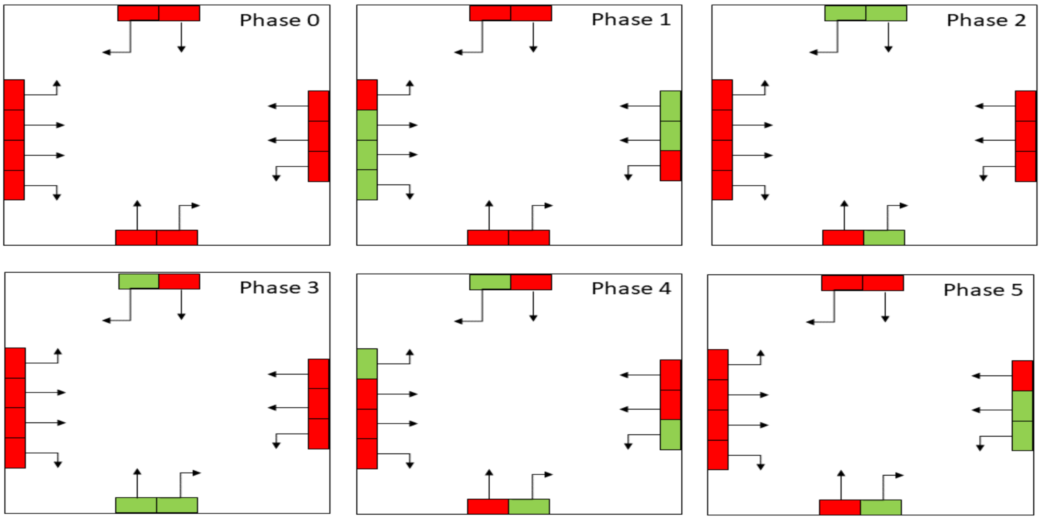
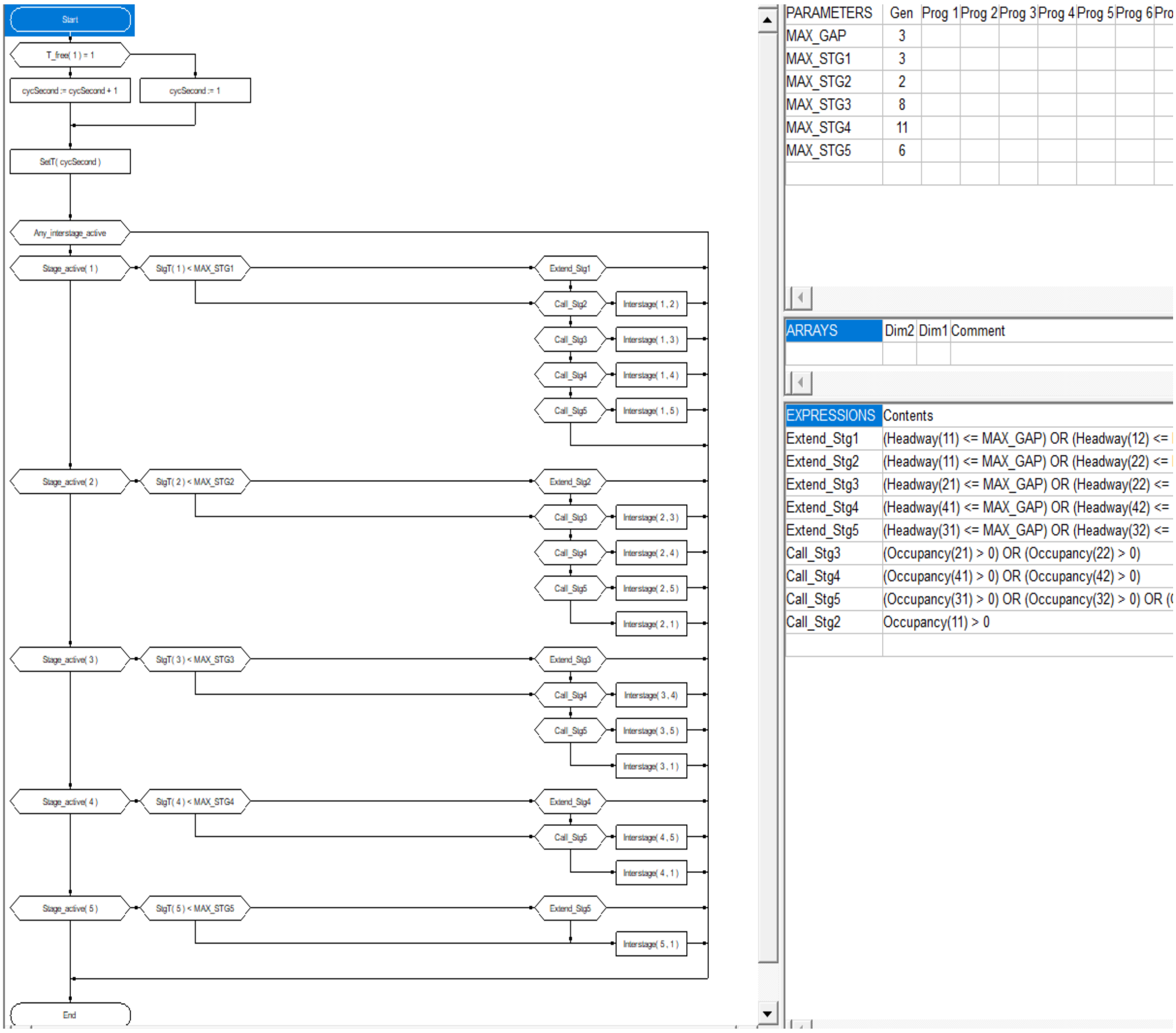


FIGURE B.2: Phase diagram intersection Weezebeeksingel – Wiekslagen (K2)

	K1		K2	
	Min. Green	**Max. Green**	**Min. Green**	**Max. Green**
Stage 1	2	7	5	24
Stage 2	5	8	3	6
Stage 3	5	7	3	6
Stage 4	5	16	3	5
Stage 5	7	13	3	5

TABLE B.1: Minimum and maximum green times for each phase of K1 and K2



PARAMETERS	Gen	Prog 1	Prog 2	Prog 3	Prog 4	Prog 5	Prog 6	Pro
MAX_GAP	3							
MAX_STG1	3							
MAX_STG2	2							
MAX_STG3	8							
MAX_STG4	11							
MAX_STG5	6							

ARRAYS	Dim2	Dim1	Comment

EXPRESSIONS	Contents
Extend_Stg1	(Headway(11) <= MAX_GAP) OR (Headway(12) <=
Extend_Stg2	(Headway(11) <= MAX_GAP) OR (Headway(22) <=
Extend_Stg3	(Headway(21) <= MAX_GAP) OR (Headway(22) <=
Extend_Stg4	(Headway(41) <= MAX_GAP) OR (Headway(42) <=
Extend_Stg5	(Headway(31) <= MAX_GAP) OR (Headway(32) <=
Call_Stg3	(Occupancy(21) > 0) OR (Occupancy(22) > 0)
Call_Stg4	(Occupancy(41) > 0) OR (Occupancy(42) > 0)
Call_Stg5	(Occupancy(31) > 0) OR (Occupancy(32) > 0) OR (
Call_Stg2	Occupancy(11) > 0

FIGURE B.3: Baseline actuated signal control with five stages, facilitated by detectors

Appendix C

Absolute priority signal control

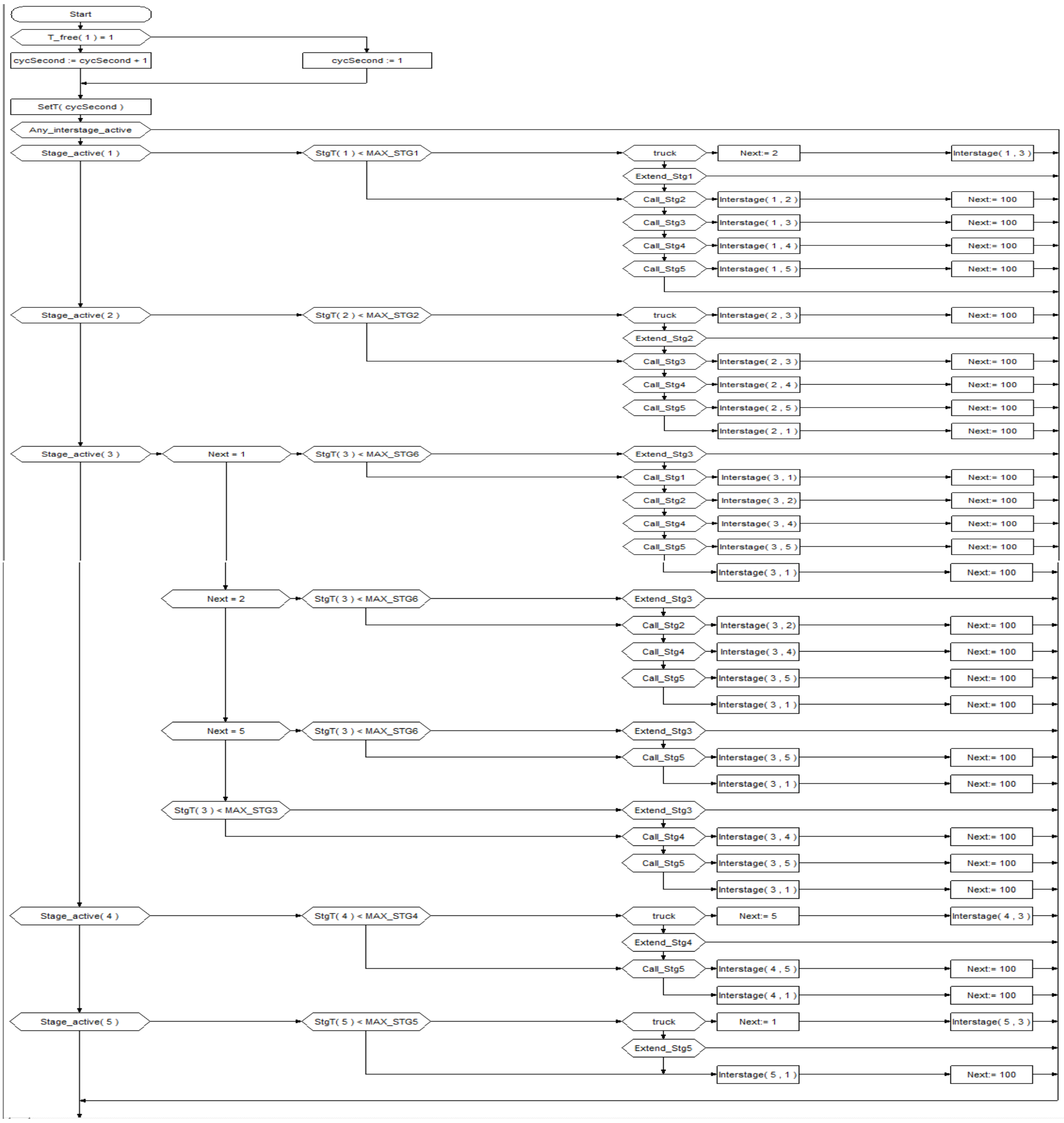


FIGURE C.1: Absolute priority signal control logic in VisVap for K1

Appendix D

Absolute priority with recovery cycle control logic

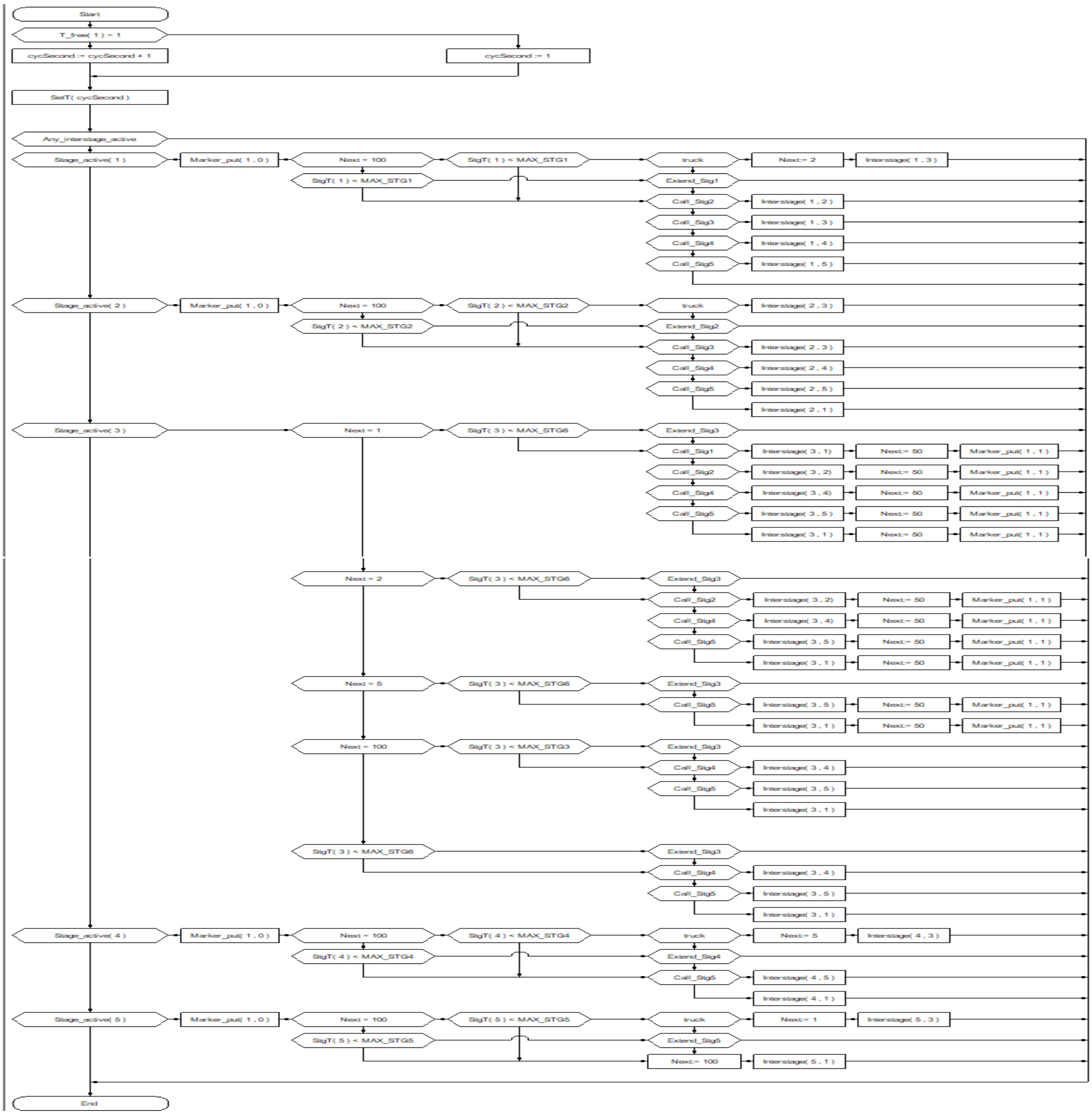


FIGURE D.1: Absolute priority with recovery cycle signal control logic in VisVap for K1

Appendix E

Platoon priority signal control

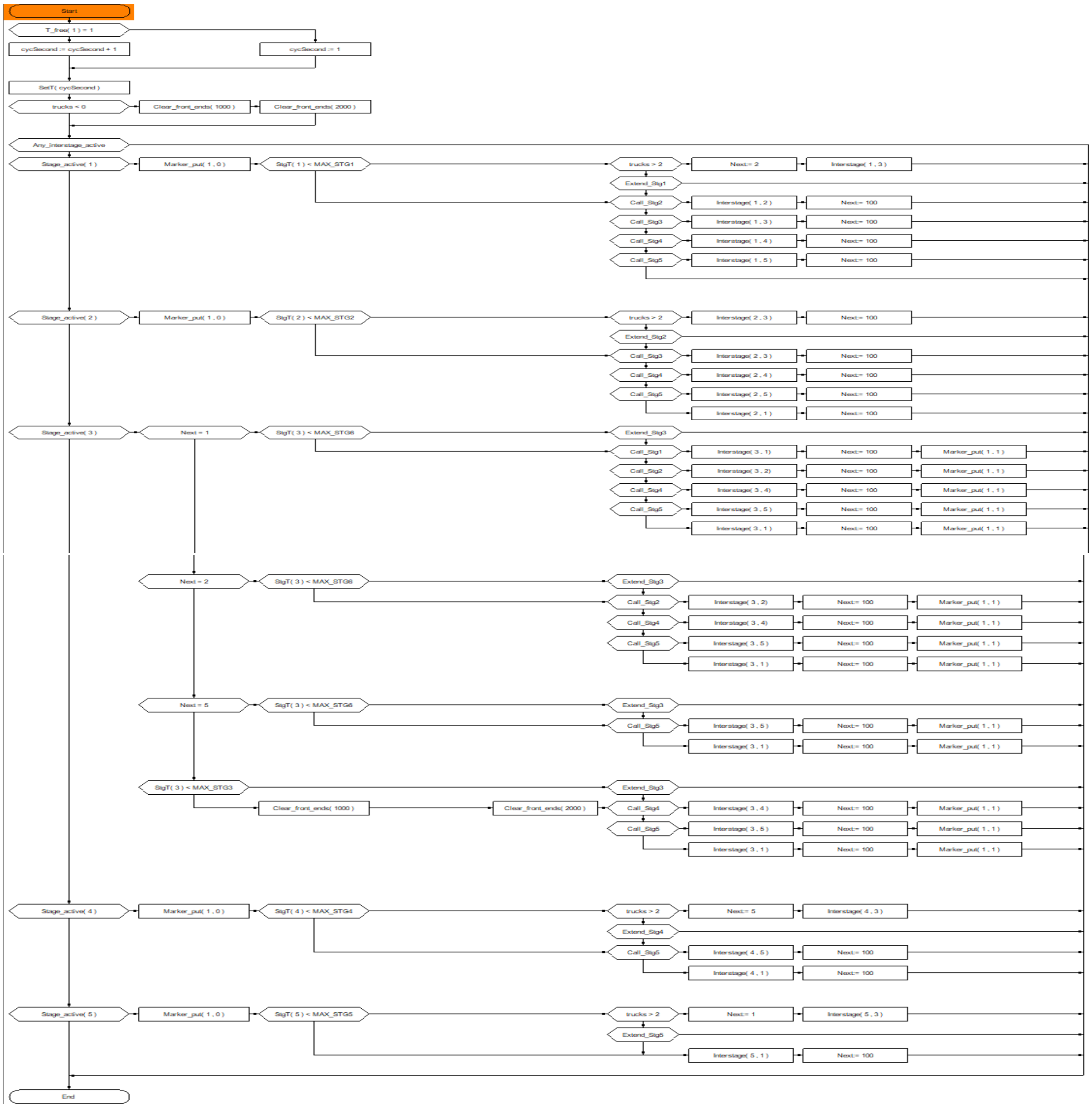


FIGURE E.1: Platoon priority signal control logic in VisVap for K1

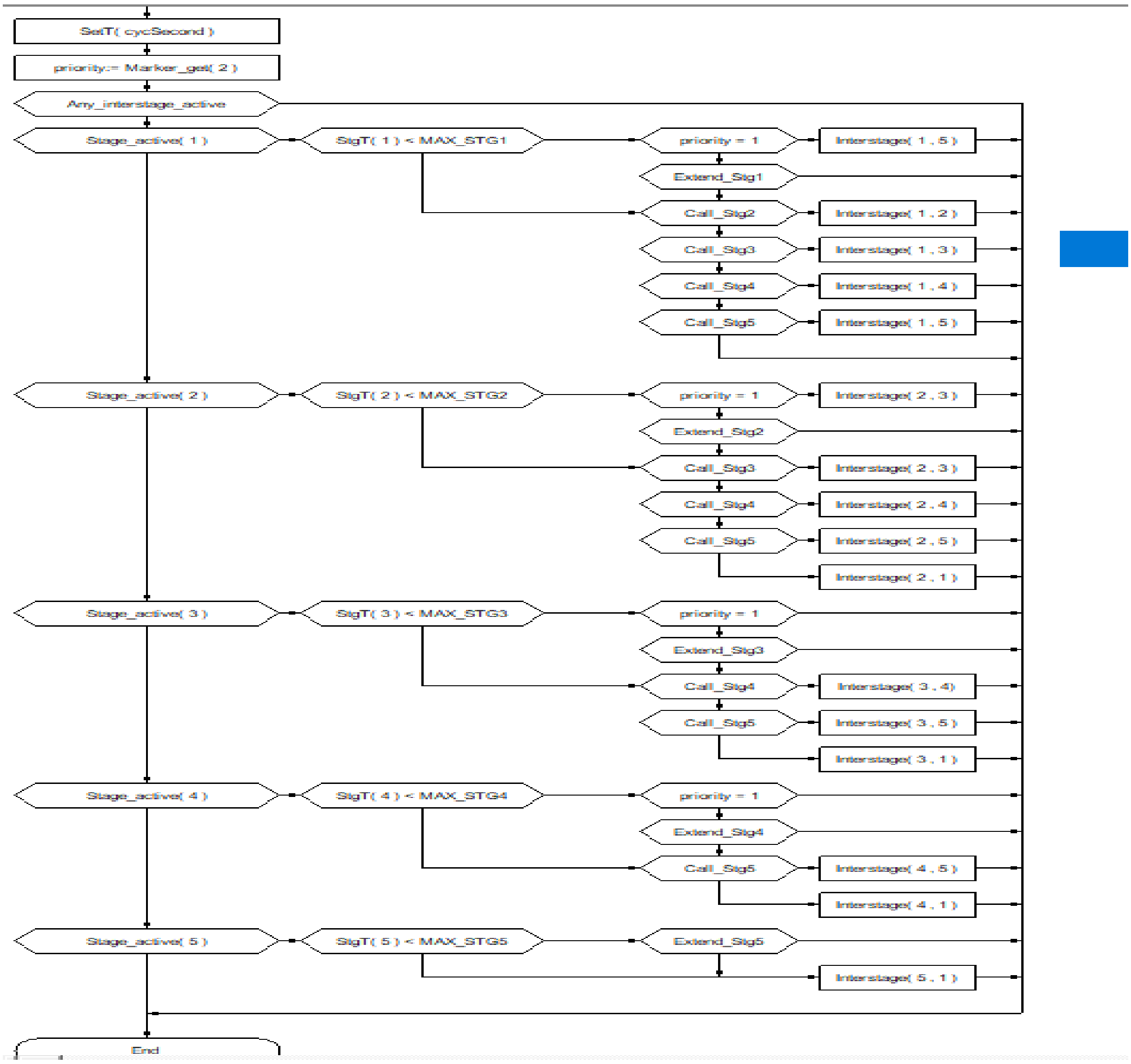


FIGURE E.2: Platoon priority signal control logic in VisVap for K2