Less is More:

Improved Traffic Flow Efficiency Effects at Vehicle-Actuated Signalised Intersections with Permitted Conflicts as opposed to Protected Conflicts

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Vialis

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Preface

After nine months of research, I proudly present my research report on the traffic flow efficiency effects of permitted conflicts as opposed to protected conflicts at vehicle-actuated signalised intersections. This research is the result of my Additional Graduation Project at Vialis, as part of my master programme Civil Engineering, track Transport & Planning at Delft University of Technology.

As stated, this research report is my Additional Graduation Project. I have chosen to do this Additional Graduation Project parallel to my regular Graduation, implying that while working on my Master Thesis, I was also working on this report. Although it was a rather demanding nine months – working on two projects simultaneously – I am happy that I did it this way. Not only did I learn to handle more than one project at the same time, I also learned what it takes to do academic research. Also, I learned how the interaction works between an academic institution, such as Delft University of Technology, and a company, e.g. Vialis, and how to negotiate when their respective interests do not align.

Permitted conflicts were always a special interest of me: why would one on a signalised intersection not control certain conflicts with traffic lights, even though it is possible to do? Why do I see permitted conflicts more abroad than in the Netherlands. These questions are two examples of my questions on permitted conflicts I had ever since I learned about traffic signal control. Of course, I learned through the years what the traffic safety consequences are of implementing permitted conflicts, and thus why protected conflicts are used, but not much attention was given to what the potential beneficial effects on the traffic flow efficiency are of implementing permitted conflicts as opposed to protected conflicts. In this research, I got the chance to do an explanatory study into these traffic flow efficiency effects.

The research could not have been at its current level if it was not for the help I received from different colleagues at Vialis, and my assessment committee and supervisor. Therefore, I would like to thank them here. First, I would like to thank Andreas Hegyi, and Maria Salomons from Delft University of Technology for their supervision from the university, and their critical feedback, information, and tips they provided me with. I also would like to thank them for their support and understanding during the past months in which I combined my Additional Graduation Project, and Master Thesis. Secondly, I would like to thank my colleagues at Vialis for creating a nice working environment, and help they gave me along the way. Thirdly, I would like to thank Jeroen Hakvoort from Vialis for offering me the chance to do both my Additional Graduation Project, and Master Thesis at Vialis, in particular on subjects that I find very interesting. But mostly, I would like to thank George Stern from Vialis for supervising me during both projects. His input, critical feedback, and support really helped raising the level of this research. Lastly, I would like to thank my family and friends for their unconditional support along the way, and the way they helped me getting my mind of my work.

Meer (Hoogstraten), 14 May 2019

Martijn M.C.J. Machielsen, BBE

SUMMARY

The objective of this research is to identify the traffic flow efficiency (TFE) effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts (PerC) at vehicle-actuated traffic signal controllers on Dutch signalised intersections, as opposed to the current practice with mainly protected conflicts (ProC), given that traffic safety conditions are met, and countermeasures are applied to ensure a safe implementation, by gaining understanding in what the potential consequences of PerCs are for traffic safety and how the potential resulting risks can be reduced, how PerCs affect the TFE, and assessing these TFE effects in a simulation study. Thereto, the question is answered what the TFE effects are, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing PerCs, when compared to implementing ProCs on signalised intersections. To answer this question, it is first investigated what PerCs exactly are, how it is applied, and what is known about this subject. The literature states that a PerC is a conflict between two crossing, or conflicting signal groups, or movements of which the crossing, or conflicting signal groups, or movements are allowed to have green at the same moment. That way, traffic of both signal groups meet at the conflict zone, and have to negotiate their conflict by themselves according to the standard priority rules. This type of conflict handling is rather common at signalised intersections, with examples from all over the world. However, in the Netherlands, road authorities are quite conservative regarding implementing PerCs. This has to do with the traffic safety consequences of implementing PerCs: most studies, and scientific publications on PerCs focus on the traffic safety impacts, in which the overall conclusion is that PerCs are less safe than signalised intersections with ProCs (conflict-free intersection). In those studies, the notes on the TFE effects are, in general, side notes, stating that PerCs might lead to shorter cycle times, and less delay, although much in-depth research has not been performed.

Therefore, this research focuses on these TFE effects. This is done using a simulation study, for a symmetric, synthetic signalised intersection, as a way to exclude geometric intersection design details affecting the number of identical conflict points. Also, several traffic safety conditions, given by the Dutch guidelines, are applied to account for the traffic safety risks, such as a pre- or synchronised start, speeds, and sight lines. Next, the simulation model (VISSIM) is validated on how it simulates the gap acceptance of PerCs. It was found that the critical gap size at PerCs in VISSIM is similar to those found in literature.

Hypotheses on the throughput and capacity, queues, and travel times and delays are tested to investigate the TFE effects of implementing PerCs as opposed to ProC. The hypotheses denote the expectations: it is expected that the (intersection) throughput, load ratio, and number of stops of movements that have to yield in a PerC increase, while the saturation flow, degree of saturation, queue lengths, number of stops of movements with priority, cycle time, and delay are expected to decrease. The reduced cycle time is also expected to be related to the number of blocks in the block sequence. The results show that the latter is the case. Furthermore, it is found that is plausible that the saturation flow decreases, just as that the load ratio increases, the queue lengths decrease, and the delay reduces. On the other hand, the results show that the hypotheses on the number of stops, and degree of saturation are implausible. For the (intersection) throughput, no decisive results were found. Therefore, it is concluded that the TFE effects of implementing PerC, as opposed to implementing ProC on signalised intersections, are positive, in that sense that it resulted in shorter cycle times, less delay, and shorter queues on average. It is recommended to investigate this further in future work, as well as the potential turning at which PerCs become contra-productive. Also, it is recommended to improve the decision-making on PerC: instead of of stating “no, unless ...”, in all cases, it is recommended to start with “yes, given that ...”, implying that permitted conflicts can be help solving TFE issues, given that certain traffic safety conditions are met. Further research contributes to this.

SAMENVATTING

Het doel van dit onderzoek is om de doorstromingseffecten (DSE) te identificeren, in termen van kruispuntbelasting en capaciteit, wachtrijen, en reistijden en vertragingen, ten gevolge van het implementeren van deelconflicten (DC) in voertuig-afhankelijke verkeersregelinstallaties op Nederlandse kruispunten, in tegenstelling tot de huidige praktijk van het toepassen van hoofdzakelijk conflictvrije kruispunten met uitsluitend reguliere conflicten (RC), gegeven dat aan verkeersveiligheidsrandvoorwaarden is voldaan, alsook dat bijbehorende maatregelen zijn toegepast, door inzicht te ontwikkelen in wat de mogelijke verkeersveiligheidsrisico's zijn, hoe die beperkt kunnen worden, hoe DC de DSE beïnvloeden, en dit te onderzoeken in een simulatiestudie. Daartoe is de vraag beantwoord wat de DSE zijn van het implementeren van DC vergeleken met PC in termen van kruispuntbelasting en capaciteit, wachtrijen, en reistijden en vertragingen. Om deze vraag te beantwoorden, is eerst onderzocht wat DC precies zijn, hoe ze zijn toegepast, wat bekend is over dit onderwerp. De literatuur definieert een DC als een conflict tussen twee kruisende, of conflicterende stromen of signaalgroepen die tezelfdertijd groen mogen hebben. Daardoor ontmoeten voertuigen van beide stromen of signaalgroepen elkaar op het conflictvlak, waar zij hun conflict dienen op te lossen volgens de thans geldende voorrangsregels. DC zijn vrij breed toegepast in de wereld, doch worden in Nederland DC minder vaak toegepast, hetgeen het gevolg is van de verkeersveiligheidsrisico's: de literatuur toont dat de meeste DC-gerelateerde studies focussen op de verkeersveiligheidsrisico's, met als algemene conclusie dat die groter zijn voor DC dan voor RC. In dergelijke studies worden de DSE hoofdzakelijk zijdelings benoemd: ofschoon DC zouden leiden tot kortere cyclustijden en dus tot minder vertraging, is weinig uitgebreid onderzoek hiernaar uitgevoerd.

Daarom focust dit onderzoek op de DSE. Daartoe is in een simulatiestudie een symmetrisch, synthetisch kruispunt onderzocht ten einde kruispuntontwerp details te minimaliseren, alsook het maximaliseren van het aantal identieke conflictzones. Verder is voldaan de gestelde verkeersveiligheidsrandvoorwaarden en zijn bijbehorende maatregelen toegepast, zoals een voor- of synchroonstart, snelheden en zichtlijnen. Bovendien is gevalideerd hoe het simulatiemodel (VISSIM) kritische hiaten van DC simuleert. Op basis van resultaten uit de literatuur, is geconcludeerd dat VISSIM dit voldoende goed doet.

Een aantal hypotheses zijn beoordeeld in VISSIM. De hypothesen beschrijven de verwachtingen van het implementeren van DC in plaats van RC voor de kruispuntbelasting en capaciteit, wachtrijen, en reistijden en vertragingen: er wordt verwacht dat de verwerkte intensiteit, de kruispuntbelasting en het aantal stops voor de voertuigen die voorrang moeten verlenen toenemen, terwijl verwacht wordt dat de afrijcapaciteit, verzadigingsgraad, wachtrijlengten, het aantal stops voor de voertuigen met voorrang, cyclustijd en vertraging afnemen. Bovendien is verwacht dat de afgenomen vertraging het gevolg is van de kortere cyclustijd. De resultaten laten dit ook zien. Daarnaast tonen de resultaten dat de hypothesen over de afrijcapaciteit, kruispuntbelasting, wachtrijlengten en vertraging waarschijnlijk correcte verwachtingen beschrijven. Desalniettemin zijn de verwachtingen in de hypothesen over het aantal stops en de verzadigingsgraad mogelijk incorrect. Voor de verwerkte intensiteit zijn de resultaten ambigu. Daarom is geconcludeerd dat de DSE van het implementeren van DC ten opzichte van RC positief zijn. Dat wil zeggen dat DC resulteren is kortere cyclustijden, minder vertraging en kortere wachtrijen. Omdat de resultaten van dit onderzoek vooral indicatief zijn, wordt aanbevolen om dit onderzoek verder uit te diepen in de toekomst. Daarnaast wordt aanbevolen voor toekomstig onderzoek om het waargenomen omslagpunt waarop DC contraeffectief worden verder te onderzoeken. Tot slot wordt aanbevolen om de besluitvorming omtrent DC in Nederland om te draaien: in plaats van "nee, tenzij…" naar "ja, mits…", hetgeen impliceert dat de toepassing van DC het potentieel heeft om verscheidene doorstromingsproblemen het hoofd te bieden, mits voldaan wordt aan verkeersveiligheidsrandvoorwaarden. Verder onderzoek zal hier aan bijdragen.

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NOTATION AND DEFINITIONS

Symbol	Unit	Domain	Description
a_{acc}	m/s²	$\mathbb{R}$	Acceleration rate
a_{dec}	m/s²	$\mathbb{R}$	Deceleration rate
d	s/pce	$\mathbb{R}$	Delay
$F(A)$	s	$\mathbb{R}$	Cumulative function of accepted gaps
$F(R)$	s	$\mathbb{R}$	Cumulative function of rejected gaps
H^{Q}	m	$\mathbb{R}$	Maximum headway in queue
h	#	$\mathbb{R}$	Number of stops
i, j	-	$\mathbb{N}$	Signal group index
K	-	$\mathbb{N}$	Set of signal groups in critical conflict group
l_{exit}	m	$\mathbb{R}$	Length of exiting vehicle
L_{enter}	m	$\mathbb{R}$	Distance from stop line to reach conflict zone
L_{exit}	m	$\mathbb{R}$	Distance from stop line to where conflict zone is cleared
L_{max}	m	$\mathbb{R}$	Maximum queue length
L	m	$\mathbb{R}$	Queue length
N	#	$\mathbb{N}$	Number of simulation runs
N^{*}	#	$\mathbb{N}$	Selected number of simulation runs
n	#	$\mathbb{N}$	Number of pilot sample simulation runs
q	pce/h	$\mathbb{R}$	Traffic flow volume
s	pce/h	$\mathbb{R}$	Saturation flow
T_{A}	s	$\mathbb{R}$	Amber time
T_{C}	s	$\mathbb{R}$	Cycle time
T_{G}	s	$\mathbb{R}$	Green time
$T_{G,\text{eff}}$	s	$\mathbb{R}$	Effective green time
T_{L}	s	$\mathbb{R}$	Internal lost time
t_{clear}	s	$\mathbb{R}$	Clearance time
t_{enter}	s	$\mathbb{R}$	Entry time to reach conflict zone
t_{exit}	s	$\mathbb{R}$	Exit time needed to clear conflict zone
t_{ps}	s	$\mathbb{R}$	Pre-start time
$t_{\text{ps,min}}$	s	$\mathbb{R}$	Minimum pre-start time
t_{r}	s	$\mathbb{R}$	Reaction time
u	-	$\mathbb{R}$	Fraction effective green per cycle
v_{exit}	m/s	$\mathbb{R}$	Speed of exiting vehicle
v^{Q}_{min}	km/h	$\mathbb{R}$	Minimum speed in queue
v^{Q}_{max}	km/h	$\mathbb{R}$	Maximum speed in queue
x	-	$\mathbb{R}$	Degree of saturation
Y	-	$\mathbb{R}$	Intersection load ratio
y	-	$\mathbb{R}$	Load ratio
z	-	$\mathbb{R}$	Student-t distribution value
α	%	$\mathbb{R}$	Reliability
θ, ϕ	-	$\mathbb{R}$	Scaling parameter
λ_{1}	s	$\mathbb{R}$	Green time start lag
λ_{2}	s	$\mathbb{R}$	Green time end lag (utilised amber)
ξ	-	$\mathbb{R}$	Normal distribution excess value
σ_{a}	-	$\mathbb{R}$	Accepted standard deviation
σ_{s}	-	$\mathbb{R}$	Standard deviation of pilot sample

1. Introduction

Road safety is mentioned as one of the major causes of worldwide mortality and morbidity (WHO, 2010). The World Health Organisation (WHO) estimated in 2009 that over 1.2 million people died due to road traffic crashes, and that approximately 50 million people were injured per year (WHO, 2009). For the European Union only, this comes down to more than 31,000 road safety related deaths (Castillo-Manzano, Castro-Nuño, & Fageda, 2014).

Because of these statistics, and the large costs associated, road safety is one of the major aspects of road traffic policies. This is especially relevant on urban roads, and intersections. The latter in particular since on intersection, traffic flows, or streams, cross, which implies a traffic safety risk. To reduce the risks at those intersections, several measures can be taken, such as roundabouts, and traffic signal control. The latter is applied when there is not enough space for a roundabout, or when the capacity of a roundabout would be insufficient. Traffic signal control aims at separating traffic flows in time, rather than spatially (CROW, 2006).

Within a traffic signal controller, one can make several choices regarding traffic flow and accessibility (traffic flow efficiency), traffic safety, and environmental factors. One of the trade-offs is between traffic flow efficiency, and traffic safety, whereas one specific measure can be considered: using permitted conflicts. For permitted conflicts it is allowed for two, or more conflicting streams to have green at the same time, and therefore cross each other at conflict zone, whereas one of the streams has priority according to the other regular traffic rules. This implies that streams with a permitted conflict are not separated in time. On the other hand, there are protected conflicts, which apply to conflicting streams that can never have green and/or amber at the same time (CROW, 2006).

1.1. Research motivation

The trade-off between traffic flow efficiency and traffic safety in terms of permitted conflicts is studied in literature, as will be discussed in chapter 3. However, most of the studies done in the past on permitted conflicts focus mainly on the traffic safety implications. Although some studies included some general conclusions on the traffic flow efficiency effects of a signalised intersection, only a limited amount statistical evidence was given for traffic flow effects. It is generally found that permitted conflicts reduce the cycle time, thereby reducing the delay as well.

On the other hand, some studies were carried out on the efficiency of permitted conflicts, although they focus on improving the efficiency of signalised intersections which already have permitted conflicts. Furthermore, such studies are mostly carried out in the U.S.A. and China, where the traffic system, including the design of the traffic systems in terms of geometric road design, is different from the European situation, in particular the Dutch situation. This is emphasised by the type of permitted conflict that is mostly the basis of those studies: in the U.S.A. and China, permitted conflicts between car streams are studied, while in Europe (e.g. the Netherlands), permitted conflicts between a car stream, and an active mode (e.g. pedestrians, bicyclists, etc., see also appendix A) stream are more commonly implemented.

Therefore, there is a knowledge gap on how efficient permitted conflicts are with respect to protected conflicts, in particular for the European situation.

1.2. Scope of the study

The research motivation states that relatively little is known of the efficiency of permitted conflicts in Europe. This already introduces the scope of this research, which is further narrowed down to Dutch signalised intersection. However, international literature is studied as well, implying that Dutch signalised intersections are solely used in the testing of permitted conflicts.

Furthermore, this research uses vehicle-actuated traffic signal controllers. This corresponds to the common practice regarding traffic signal control in the Netherlands. That is, fixed time traffic signal controllers are not usually applied.

1.3. Research objective and questions

The objective of this research is to identify the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts at vehicle-actuated traffic signal controllers on Dutch signalised intersections, as opposed to the current practice with mainly protected conflicts, given that traffic safety conditions are met, and countermeasures are applied to ensure a safe implementation, by gaining understanding in what the potential consequences of permitted conflicts are for traffic safety and how the potential resulting risks can be reduced, how permitted conflicts affect the traffic flow efficiency, and assessing these traffic flow efficiency effects in a simulation study.

In order to reach the research objective, the following main research question and corresponding sub-questions are formulated:

What are the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts, when compared to implementing protected conflicts on signalised intersections?

- *What are permitted conflicts?*
  - What are the conflict types on signalised intersections?
  - What are the types of permitted conflicts?
  - How are conflicts at signalised intersections implemented in practice, in an international context?
- *What are the known consequences of permitted conflicts?*
  - What are the consequences of permitted conflicts in relation to traffic signal controller design?
  - What are the traffic safety implications of permitted conflicts?
  - How are the traffic safety risks mitigated, and/or reduced?
  - What is known about the traffic flow efficiency effects of permitted conflicts?
- *What are the expected traffic flow efficiency effects of permitted conflicts?*
  - Which performance indicators can be used to investigate the traffic flow efficiency effects of permitted conflicts?
  - Which effects are expected in relation to intersection throughput and capacity?
  - Which effects are expected in relation to queues?
  - Which effects are expected in relation to travel times and delays?
- *How can permitted conflicts be simulated?*
  - How valid is VISSIM when simulating permitted conflicts?
- *How do permitted conflicts affect the traffic flow efficiency with respect to protected conflicts?*
  - What are the effects of permitted conflicts with respect to protected conflicts in relation to intersection throughput and capacity?
  - What are the effects of permitted conflicts with respect to protected conflicts in relation to queues?
  - What are the effects of permitted conflicts with respect to protected conflicts in relation to times and delays?

1.4. Research steps

The research model, visualising the research steps, is based on the aforementioned research questions. The research model is shown in Figure 1-1, in which the red boxes represent the steps. The lined boxes are the actions in that step. The output of one step is then input for a following step.

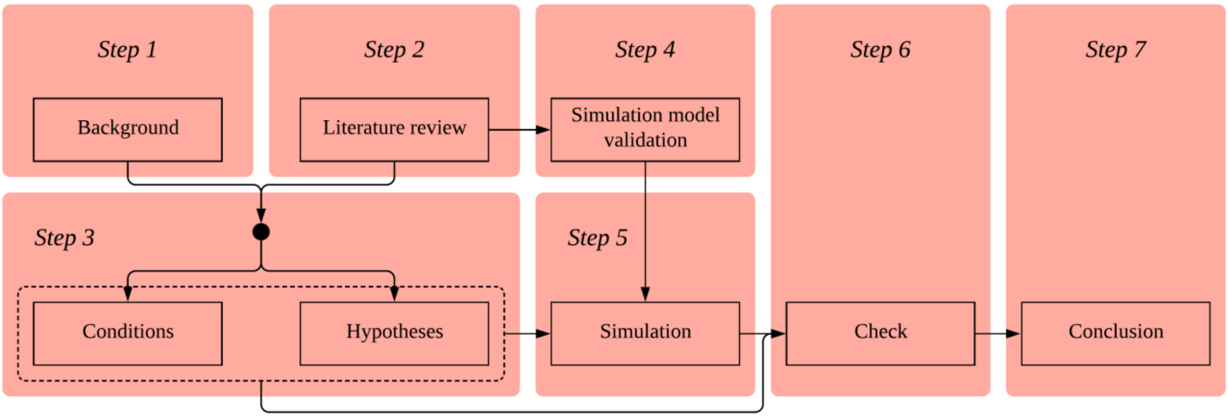


Figure 1-1 | Research model.

The research steps are as enumerated below:

1. *Background*: first, the question is answered what permitted conflicts actually are. In a more general way, the background of conflict types at signalised intersection, in particular permitted conflicts, is discussed. This includes a short literature review of (international) guidelines to gain understanding in conflicts at signalised intersections, and how they are implemented in practice. This is used to formulate the hypotheses, and conditions in step (3).
2. *Literature review*: parallel to the background, a literature study is done on the known consequences of permitted conflicts. This includes a review of various international, scientific studies on the effects of permitted conflicts. Besides, a literature study is done on how permitted conflicts can be simulated. The result of this step is therefore (a) an overview of the known consequences, which is input for step (3) to formulate the hypotheses, and conditions, and (b) insight in how the simulation model can be validated in step (4).
3. *Conditions and hypotheses*: given the background, and known consequences of permitted conflicts, the conditions are listed that are to be accounted for when implementing permitted conflicts. These conditions relate to the traffic safety risks in particular, and how they can be reduced/mitigated. Also, hypotheses are formulated that describe the expected traffic flow efficiency effects. Thereto, it is first listed which performance indicators are needed. These performance indicators are based on the general assessment aspects intersection throughput and capacity, queues, and travel times and delays. The output of this step is thus an overview of the traffic safety conditions, and hypotheses that are tested in the simulation study in step (5).
4. *Simulation model validation*: this step is an intermediate step used to validate the simulation model as used in step (5). The validation makes use of the literature review results. In the validation, the used simulation software (VISSIM) is tested on how well it simulates permitted conflicts, as a way to establish a ground truth. To do so, the validation uses real-life data as found in scientific literature in step (2). The output of this step is then a validated simulation model that can be used in the next step.
5. *Simulation*: this step focuses on the simulation study in VISSIM. The simulation study aims at identifying the traffic flow efficiency effects, that are investigated in the next step. The simulation study focuses on the effects on intersection throughput and capacity, queues, and travel times and delays.

6. *Check*: this step checks whether the simulation study results of step (5) correspond to the hypotheses of step (3). In other words, it is checked whether the hypotheses are accepted, or rejected. This is a measure for the traffic flow efficiency effects, used to conclude the research in the next step.
7. *Conclusion*: the simulation results show the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts, when compared to implementing protected conflicts on signalised intersections. Also, the research questions, as listed above, are answered explicitly, and recommendations regarding further implementation of permitted conflicts, and for future work are given.

1.5. Guide to the report

The report is structured based on the research steps as listed above. That is, each chapter discusses one, or two of the steps mentioned earlier.

The report starts with chapter 1, which serves as introduction to the report. The background of permitted conflicts is discussed in chapter 2. Chapter 3 focuses on the literature review in terms of the known consequences of permitted conflicts. In chapter 4, the traffic safety conditions, and traffic flow efficiency hypotheses are listed. This also includes a description of the considered performance indicators. Chapter 5 discusses the validation of the simulation model, thereby including the related literature review, and simulation study. In chapter 6, the permitted conflicts are simulated, and it is checked whether the found results correspond to the earlier formulated hypotheses. Lastly, the report is wrapped up in chapter 7, where the research questions are answered, and recommendations are given on both further implementation of permitted conflicts, and future work.

2. Background of permitted conflicts and protected conflicts

To make intersections safe, one can separate traffic flows spatially, and/or in time. The latter implies that the traffic flows make use of the same infrastructure at an given point – the conflict zone – but not at the same time: first one stream of traffic uses that infrastructure, then the other. To do so, traffic signal control can be used. A traffic signal controller facilitates the aforementioned separation of traffic flows in time on conflict zones (CROW, 2006). This introduces the term conflict. It is customary that crossing streams are conflicting streams. Also, streams that converge are considered conflicting streams.

In this chapter, the different terms – conflicts, conflict types, permitted conflicts, and protected conflicts – are discussed in depth, to give an overview on what these terms mean. Also, the current practice with regard to the conflict types is discussed, based on the (international) guidelines, and scientific publications. The chapter concludes with the main findings.

2.1. Conflict types

First, it must be noted that not every conflict is identical. There are two types of conflicts: protected conflicts and permitted conflicts. Protected conflicts apply to conflicting streams that cannot have green and/or amber at the same time. On the other hand, for streams with a permitted conflict, it is allowed to have green and/or amber at the same time, implying that these streams are not separated in time. Indeed, permitted conflicts allow two, or more conflicting streams to meet each other on the conflict zone, where the regular priority rules apply in that case (CROW, 2006). In the Swedish guidelines, it is specified which conflicts *might be* treated as permitted conflicts, and which *have to be* treated as protected conflicts. For instance, the guidelines state that streams that cross perpendicularly have to be treated as protected conflicts, see Figure 2-1 (Nordlinder, Andersson, & Kronborg, 2017).

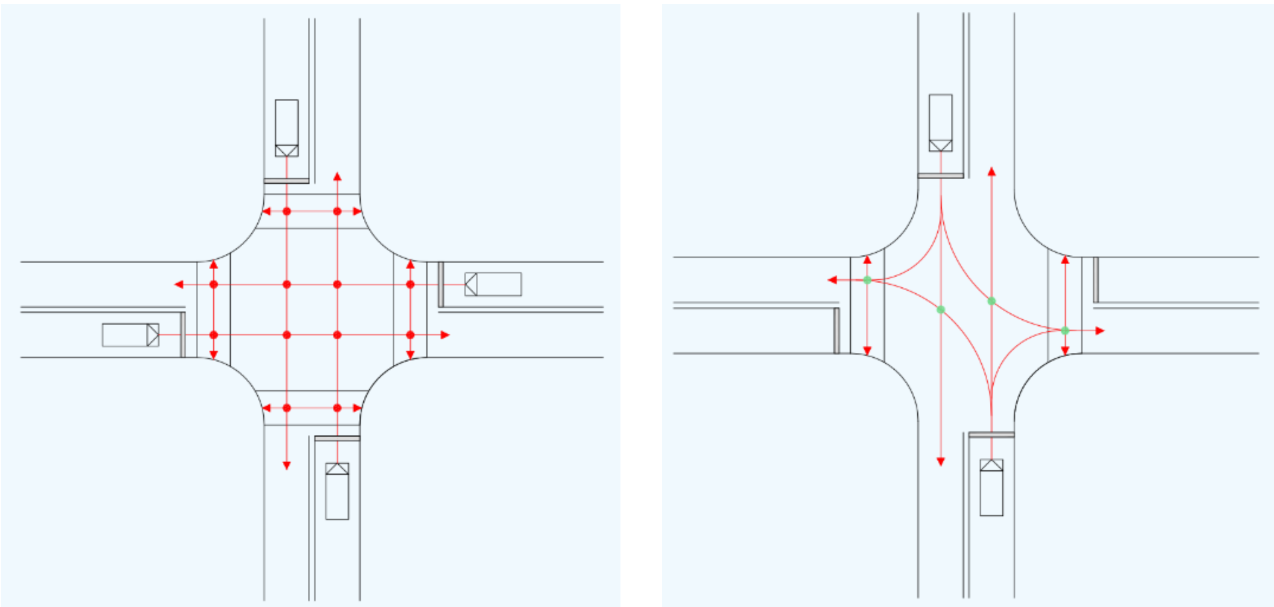


Figure 2-1 | Conflicting streams that *have* to be treated as *protected* conflicts (left), and *might* be treated as *permitted* conflicts (right) (Nordlinder, Andersson, & Kronborg, 2017).

Within the domain of permitted conflicts, there exists another specification of such conflicts: (i) permitted conflicts between car streams, or signal groups (signal groups with mainly motorised traffic), and (ii) permitted conflicts between car signal groups and active mode signal groups (signal groups with pedestrians, bicyclists, etc., see appendix A). In both cases it holds that the regular traffic regulations on priority are in order when the signal groups meet at the conflict zone. Therefore, permitted conflicts are allowed, and used in two cases, based on the regular priority rules (CROW, 2006):

1. Parallel car signal groups (permitted conflict type 1): a through-going car signal group has green at the same moment as a left turning car signal group coming from the opposite direction. In this case, the turning car signal group has to yield for the through going car signal group, see Figure 2-2a;
2. Parallel car signal group with active mode signal group (permitted conflict type 2): a left or right turning car signal group has green at the same moment as a through-going active mode signal group. Now, the car signal group has to yield for the through going active mode signal group, see Figure 2-2b.

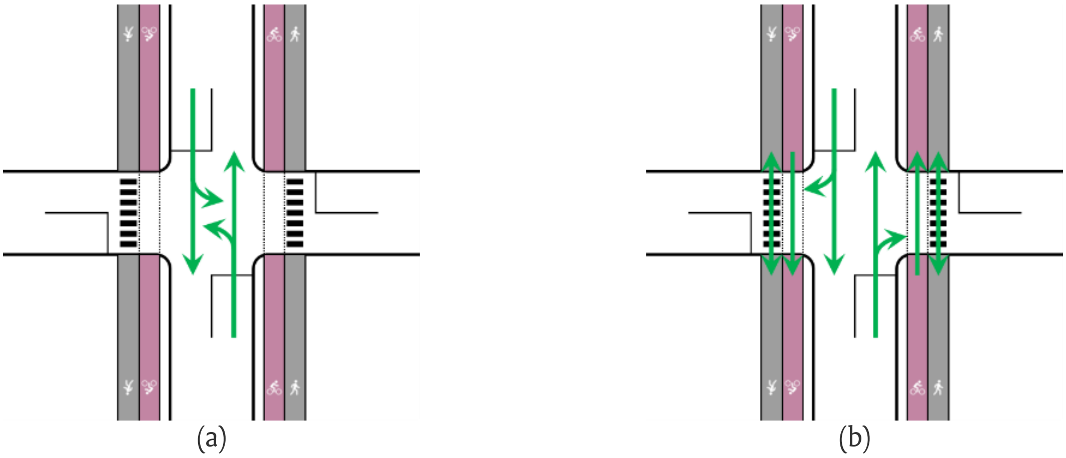


Figure 2-2 | Illustration of permitted conflicts (a) type 1, and (b) type 2.

In international perspective, there are two more types of permitted conflicts, which are combined with protected conflicts (Hauer, 2004; Shebeeb, 1995; TRB, 2000; TRB, 2012), which are usually based on permitted conflict type 1:

3. Leading protected-permitted: initially, the conflict is a protected conflict. However, this protected phase expires, meaning that a conflicting signal group (b) receives green during the initial green phase of signal group (a), implying a change from protected conflict to permitted conflict during one green phase (Figure 2-3);

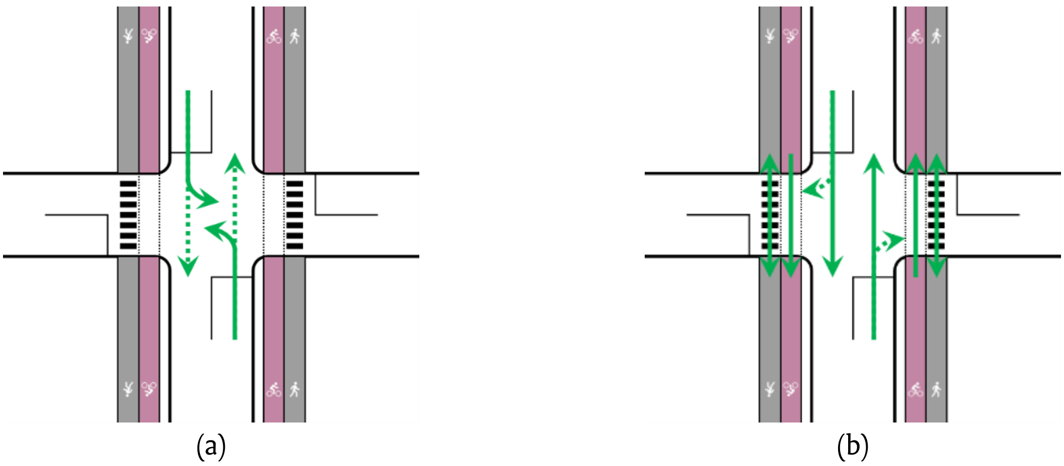
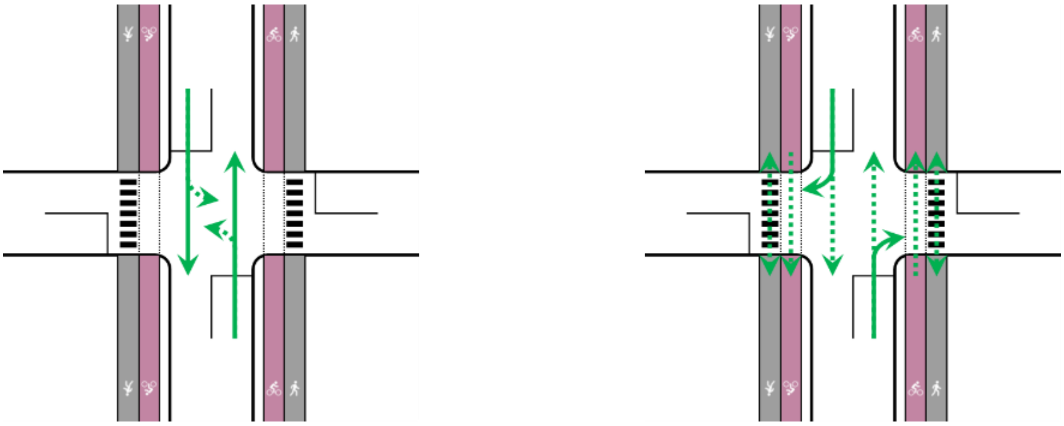


Figure 2-3 | Illustration of permitted conflict type 3, based on type 1 (a), and type 2 (b) – the dotted arrows represent green phases of signal groups that are not yet present at the start of the green phases of the signal groups visualised as solid arrows.

4. Lagging protected-permitted: initially, the conflict is permitted, until this phase expires, turning the phase into a protected conflict (Figure 2-4). Thus, the conflict changes from permitted to protected during one green phase.



(a) (b)

Figure 2-4 | Illustration of permitted conflict type 4, based on type 1 (a), and type 2 (b) – the dotted arrows represent green phases of signal groups that are terminated before the green phases of the signal groups with solid arrows.

Additionally, Dallas phasing could be considered. Dallas phasing is exclusively relevant for permitted conflict type 1, and the permitted conflicts types based on type 1. Where usually two opposing left-turning signal groups are not in conflict with each other, Dallas phasing does bring them in conflict. This implies that a left-turning signal group (a) has to yield for an opposing through-going signal group (b), and the opposing left-turning signal group (c) as well (Shebeeb, 1995; TRB, 2012), see Figure 2-5.

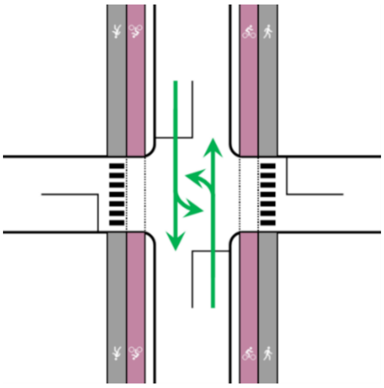


Figure 2-5 | Illustration of permitted conflict type 1 with Dallas phasing.

Lastly, a special type of permitted conflicts is (5) the use of hook turns. Although the principle of hook turns is commonly applied for active modes, for instance in the Netherlands, New Zealand, and Germany, hook turns for car traffic are implemented as well, for instance in Melbourne, Australia. In the case of hook turns, car traffic is only allowed to turn left from the right lane (assuming a right-driving system), while through-going traffic drives on the left lane. Left-turning traffic than has to wait on the intersection for the parallel through-going streams, see Figure 2-6a. Hook turns are commonly applied on streets where a tram track is present to reduce the delays of trams caused by turning car traffic, and are implemented in Melbourne even exclusively on streets with a tram track as the median (Currie & Reynolds, 2011). There are examples in other cities, and countries as well, e.g. Gothenburg, Sweden, though there, hook-turns might be controlled as protected conflicts see Figure 2-6b.

(a) (b)

Figure 2-6 | Illustrations of permitted conflict type 5 (hook turns) in a right-driving system, with (a) a schematic overview, and (b) implementation in practice in Gothenburg, Sweden.

2.2. Implementation in practice

Permitted conflicts are applied at various signalised intersections over the world. Therefore, studies on permitted conflicts are performed in various countries. This section explores the implementation in practice of permitted conflicts, protected conflicts, and conflict-free signalised intersections (intersections with only protected conflicts), in an international context, using different studies, and guidelines.

2.2.1. The Netherlands

The use of permitted conflicts in the Netherlands, referred to as “deelconflicten”(literally “partial conflicts” in Dutch), is discussed in the guidelines as given by (CROW, 2006). The guidelines are quite clear about the use of permitted conflicts: it is allowed, given that certain conditions are met, e.g. sightlines, traffic flow, speeds, etc., as discussed more elaborately in section 3.2. Although there is no database of which Dutch signalised intersections have permitted conflicts, the general practice is to use only protected conflicts (CROW, 2006; Van Herck, 2013). However, a questionnaire by (Wilson, 1999) found that only 28% to 29% of 140 Dutch road authorities never implements permitted conflicts. The same questionnaire showed that 65% to 67% only take permitted conflicts into consideration depending on the situation, which implies that the general practice is not to implement permissive phasing. Still, most of these permitted conflicts are type 2 (cars versus active modes); an example is shown in Figure 2-7 on the next page. Permitted conflicts type 1 (cars versus cars) are, in general, more rare in the Netherlands. Although there is no database with the different signalised intersections, and the applied conflict types, examples of signalised intersections with permitted conflicts type 1 are observed in Amsterdam, The Hague, and Tilburg, among others.

2.2.2. Europe

2.2.2.1. Belgium

The Belgian general policy is, in contrast to the Netherlands, that not all conflicts on signalised intersections are protected conflicts (Allaert, 2007; AWV, 2011; Dreesen, 2005). Indeed, most signalised intersections are so called two-phase-controllers, which only separate streams in time that cross perpendicular. This means that parallel streams receive green at the same time. This implies that permitted conflicts of both types are implemented in Belgium, see also Figure 2-8 on the next page. Moreover, it has been observed on several intersections, that permitted conflicts of type 4 are implemented, based on permitted conflict type 2 (car stream with active mode stream). The Belgian traffic signal control guidelines discusses these kinds of conflicts as permitted, or literally “in the twilight zone”, meaning that is up to the traffic engineer to decide whether or not a conflict is a protected conflict (AWV, 2009). Nevertheless, in recent years, the Belgian road authorities, in Flanders in particular, are implementing complete conflict-free intersections (De Pauw, Van Herck, Daniels, & Wets, 2014; Van Herck, 2013).

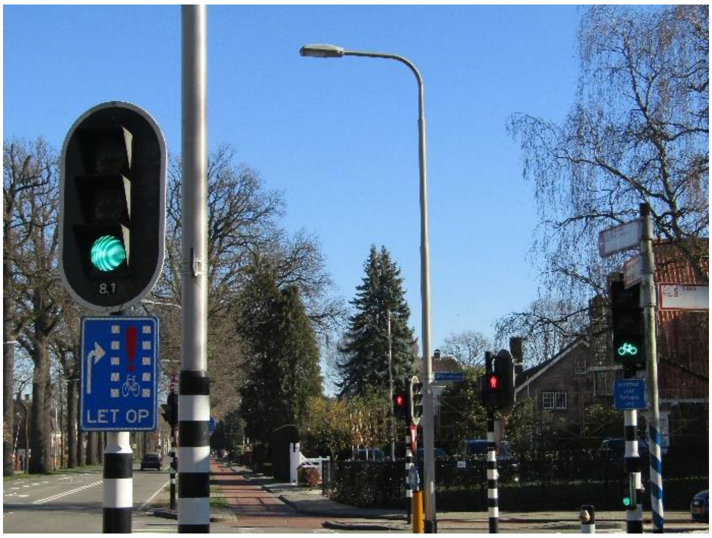


Figure 2-7 | Example of permitted conflict type 2 in practice in the Dutch city of Tilburg.

(a) (b)

Figure 2-8 | Examples of permitted conflicts in Belgium: (a) **type 1 (Zelzate), and** (b) **type 2 (Maldegem).**

2.2.2.2. Germany and Austria

In Germany, it is also common policy to implement permitted conflicts of both types 1 and 2, given certain conditions, including the conditions as in the Netherlands such as sightlines and traffic flow, whereas permitted conflicts type 2 are considered as standard conflicts, since it reduces the delays. Nonetheless, the German guidelines state that two-phase-controllers are not desired given the traffic safety implications (FGSV, 2010). The same holds for Austria (Pfaffenbichler, 2007).

2.2.2.3. Scandinavia

In Denmark, Norway, and Sweden, permitted conflicts are referred to as "sekundære konflikter", "sekundærkonflikt", and "sekundärkonflikt" respectively, literally secondary conflicts, whereas only permitted conflict types 1 and 2 are considered, see also Figure 2-9 on the next page. However, the implementation of permitted conflicts is in general only preferred because of capacity and traffic safety reasons. Therefore, the implementation of permitted conflicts should always be done after careful consideration in which conditions similar to the Dutch conditions are evaluated (Madsen, et al., 2012; Statens Vegvesen, 2012; Vägverket & Svenska Kommunförbundet, 2004). Moreover, in Sweden it is explicitly stated that permitted conflicts of types 3 and 4 are not allowed, to prevent confusion of drivers (Nordlinder, Andersson, & Kronborg, 2017).

(a) (b)

Figure 2-9 | Examples of permitted conflicts from practice, in Gothenburg, Sweden: (a) type 1, and (b) type 2.

2.2.2.4. France

The French guidelines discuss compatible and incompatible streams, whereas the latter are always protected conflicts. All other streams do either not have a conflict, or are considered as permitted conflicts. It is common practice to allow permitted conflicts of both type 1 and 2. However, it is also stated that the traffic engineer must decide whether two conflicting streams are either compatible (permitted conflict), or incompatible (protected conflict) (DSCR, 2012).

2.2.2.5. Italy

In Italy, the same terms as in France are used – compatible, and incompatible streams. There is one major difference, however, because in Italy permitted conflicts of type 1 are not allowed. Indeed, only permitted conflicts type 2 are allowed, as those conflicts can be regulated with an extra warning sign. Also, for these types of permitted conflicts, the green phase of the active mode should preferably start before, but no later than the conflicting car stream. All other conflicts are considered as incompatible streams and should therefore be signalised in a conflict-free manner (Camus, 2001).

2.2.3. United States of America

The U.S.A. has done many studies on protected and permitted conflicts of all four types, including Dallas phasing, implying that all permitted conflict types are implemented in the U.S.A. These studies investigated the benefits and risks of permitted conflicts over protected conflicts. Koonce, et al. (2008) focus on the permitted conflicts of types 1, 2, 3, and 4, though type 2 is less pronounced. This also the case in the Highway Capacity Manual (TRB, 2000; TRB, 2012), though in the latter, Dallas phasing is not mentioned.

2.2.4. China

In the paper of Lam, Poon, & Mung (1997), in which an integrated model for lane-use and signal-phase designs is proposed, they introduce the common practice in China on conflicts, in particular incompatible streams, similar to the terminology in France, and Italy. Their conflictmatrix suggests that permitted conflicts of both types 1 and 2 are allowed, and that those permitted conflicts are standard practice. In more recent studies of Zhou & Zhuang (2012), and Li & Sun (2016), it is stated that these permitted conflicts are still being implemented. However, they state that additional measures should be taken to improve the throughput of the intersection, especially regarding permitted conflicts type 1.

2.3. Main findings

The main findings regarding the background of permitted conflicts are as enumerated below:

- At signalised intersections, there are different types of conflicts between crossing streams, or signal groups: permitted conflicts, and protected conflicts. Traffic on signal groups with a permitted conflict are allowed to meet each other at the conflict zone during their green phase, while traffic on signal groups with a protected conflict are separated in time. That is, they do not meet at the conflict zone during their green phase. In the Swedish guidelines, it is stated explicitly that signal groups that cross each other perpendicularly have to be treated as protected conflicts.
- Within permitted conflicts, a further distinction can be made, based on the modes that are involved. For this research, only two permitted conflict types are relevant:

  1. Parallel car signal groups: a through-going car signal group has a permitted conflict with a left-turning car signal group from the opposite direction;
  2. Car signal group with a parallel signal group for active modes: a left-, or right-turning car signal group has a permitted conflict with a parallel through-going signal group for active modes.

- In practice, permitted conflicts are quite common. That is, in most countries, permitted conflicts are widely implemented. In the Netherlands, road authorities are more conservative with implementing permitted conflicts, especially permitted conflict type 1; permitted conflict type 2 is more often implemented in the Netherlands, in particular on urban signalised intersections, e.g. in Amsterdam, among others. Also, in the Netherlands, guidelines are formulated on how permissive phasing can be implemented safely. In other European countries, e.g. Belgium, Germany, Austria, the Scandinavian countries, France, and Italy, both types of permitted conflicts are implemented. These countries use national guidelines to ensure a safe implementation, thereby sometimes even prohibiting a certain permitted conflict type. In the U.S.A., permitted conflict type 1 is very common, as stated in the national guidelines as well. The same goes for China, based on research that has been done there.
- In the U.S.A., and China, quite a lot of research is done on the traffic safety impacts of permitted conflicts, especially permitted conflict type 1. These researches focus on the benefits, and risks of permitted conflicts with respect to protected conflicts.

3. Known consequences of permitted conflicts

The evaluation of permitted conflicts has been a popular research topic for many years, and still is. This implies that multiple studies are done on the consequences of permitted conflicts. Indeed, the implementation of permitted conflicts has several consequences in terms of (i) the design of a traffic signal controller, (ii) traffic safety, and (iii) traffic flow efficiency. This chapter discusses those studies, scientific publications, and guidelines. Therefore, the focus of this chapter is on what is currently known about the consequences of the use of permitted conflicts versus protected conflicts. Furthermore, this chapter discusses the relevant implications for (i) the design of a traffic signal controller, (ii) traffic safety, and (iii) traffic flow efficiency. The chapter concludes with a brief overview of the main findings.

3.1. Traffic signal controller design

The publications on the impact of permitted conflicts on the design of a traffic signal controller are rather scarce. Indeed, most studies focus on traffic safety. This implies that not much is published on the traffic signal controller design consequences. Nevertheless, Gibby, Washington, & Ferrara (1991) mention that for an efficient, and safe implementation of protected conflicts, a separate lane for left-turning traffic is needed, since the through-going, and left-turning streams can be served in different blocks. When permitted conflicts are implemented, mixed use of a lane (both turning, and through traffic on the same lane) might be allowed.

Other studies mention the impact of implementing permitted conflicts on the cycle time, with respect to delays: if the cycle time is longer, the delay is higher as well. Upchurch (1986) mentions this explicitly. Similar notions were made by Stamatiadis, Agent, & Bizakis (1997), and Hauer (2004).

3.2. Traffic safety

As stated before, most of the research related to permitted conflicts focus on the traffic safety consequences, and implications. Moreover, most of the studies are carried out in the U.S.A., where the focus is mostly on the permitted conflicts type 1. Nevertheless, some studies investigated the traffic safety implications of permitted conflicts 2 as well. Also, the way permitted conflicts are displayed with the traffic lights, and traffic signs is investigated. Lastly, the traffic signal control guidelines mention the traffic safety implications explicitly. All these aspects are discussed in this section.

3.2.1. Research publications

The research on the traffic safety effects of permitted conflicts focus on multiple aspects of permitted conflicts. First, the studies, and publications that focus on the different types of conflicts are discussed. Secondly, the way the traffic signal displays affect driving behaviour at signalised intersections with permitted conflicts is investigated. Lastly, the overall traffic safety effects, in terms of crashes, traffic safety surrogate safety measures, and crash risk are discussed.

3.2.1.1. Left-turning permitted conflicts

The permitted conflicts types related to left-turning traffic are the types 1, 3, 4, and 5. In most studies, the different types are evaluated at once, with the left-turning conflicts as overall permitted conflicts.

3.2.1.1.1. Traffic safety evaluation

The different types of left-turn phasing, in this research categorised in permitted conflicts types 1, 3, and 4, is investigated by Upchurch (1991) by comparing the different crash rates – number of crashes with respect to the traffic flow volume – per permitted conflict type. For his statistical evaluation, he included over 500 signalised intersections in Arizona, U.S.A., in which he related the crash rate to the traffic flow volume per day for left-turning streams. His conclusion was that the safest way to signal left-turning traffic, was conflict-free (protected conflicts), followed by types 4, and 3, implying that an exclusively permitted left-turn phase (type 1) has the highest crash rate. His results were part of the literature study of Hauer (2004) who found comparable results in other studies as well, including the study of Shebeeb (1995). In one of those studies, the traffic safety implications on high-speed isolated signalised intersections were investigated, thereby including the effects of use of protected conflicts versus permitted conflicts for left-turning traffic. This study concluded that on such high-speed isolated signalised intersections protected conflicts for left-turning traffic improve the traffic safety at the intersection (Gibby, Washington, & Ferrara, 1991).

Several other studies developed models to examine the traffic safety effects of different traffic safety measures at signalised intersections. Some of these studies explicitly focused on left-turning permitted conflicts. For instance, Shadah, Saccomanno, & Persaud (2015) investigated the effect of changing permitted conflict type 1 in type 3, thus from permissive phasing into leading protected-permissive phasing, on the time to collision using a model study with VISSIM. They found that this countermeasure improves the traffic safety of a signalised intersection. The same results were found by Stamatiadis, Tate, & Kirk (2016), also using a model study with VISSIM, and Amiridis, Stamatiadis, & Kirk (2017) and Yang, Shi, Yu, & Zhou (2018), using analytical models.

3.2.1.1.2. Hook-turn permitted conflicts

The traffic safety and operational impacts of hook-turns as permitted conflicts are investigated by Currie & Reynolds (2011). In terms of traffic safety, they found that signalised intersections with hook-turns perform better on crash rate than intersections without hook-turns. Nevertheless, they found that the largest risk of this type of permitted conflicts is driver understanding, since it is a rather unconventional way to control permitted conflicts. However, they also state that due to potential driver misunderstanding, drivers might be tempted to avoid hook-turn intersections, thereby reducing the crash risk in terms of exposure.

3.2.1.2. Left-turn signal displays

To warn drivers that a conflict on a signalised intersection is a either a protected or permitted conflict, thus whether or not drivers might expect opposing traffic at the conflict zone, different left-turn signal displays might be used, each with its own corresponding driver behaviour. The study by Noyce, Fambro, & Kacir (2000) investigated those effects, and found that in general, the left-turn signal display does not cause unsafe driver behaviour. However, when a traffic signal without an arrow symbol is used, drivers might misinterpret this as a protected green phase, implying a traffic safety risk. Other traffic safety risks were caused due to hesitation of left-turning drivers, and potential driver work overload in relation to a five-lens traffic signal. Lastly, they formulate some recommendations on which displays should be used.

3.2.1.3. Permitted conflicts in general

In more general studies on permitted conflicts, permitted conflicts of both types 1 and 2 are investigated. The latter in particular is investigated by Welleman (1980) who found no statistical significant effect on traffic safety when changing from permitted conflicts to protected conflicts, in the Netherlands. However, he also stated that this mostly related to red-light running.

In Belgium, the study of Dreesen (2005) concluded that a conflict-free signalised intersection (protected conflicts) is significantly safer than signalised intersections with permitted conflicts, regardless of the type, based on a literature study of international publications. Although Dreesen (2005) states the results of these studies cannot be one-on-one copied to the Belgian situation, the general trend is quite clear. These results are also found by Van Herck (2013), and De Pauw, Van Herck, Daniels, & Wets (2014).

Lastly, Li & Sun (2016) developed a cellular automata model to predict the effect of lane sharing, and conflict type at signalised intersections. Using their model, they found that permitted conflicts have a higher crash risk than protected conflicts.

3.2.2. Guidelines

Several scientific publications propose guidelines with respect to the use of permitted conflicts as well, in particular in relation to left-turning traffic (permitted conflict types 1, 3, and 4). Those guidelines are based on (previous) research, and usually state conditions regarding the use of permitted conflicts versus protected conflicts. The conditions per international publication are as listed in Table 3-1. In this table, it can be seen that the studies of Upchurch (1986), and Stamatiadis, Agent, & Bizakis (1997) were part of the literature study of Hauer (2004), among other publications. The conditions of Upchurch (1986) are included in a decision tree, based on his finding that permitted conflict type 1 has a crash rate over three times as high as protected conflicts – for permitted conflict type 3, the crash rate is twice as high as protected conflicts. In a similar way, Davis, Moshtagh, & Hourdos (2016) proposed a relative risk model, with similar results as Upchurch (1986). The results, and guidelines proposed by Upchurch (1986), and Stamatiadis, Agent, & Bizakis (1997) were part of the literature study of Hauer (2004), among other publications.

Table 3-1 | Conditions per scientific publication.

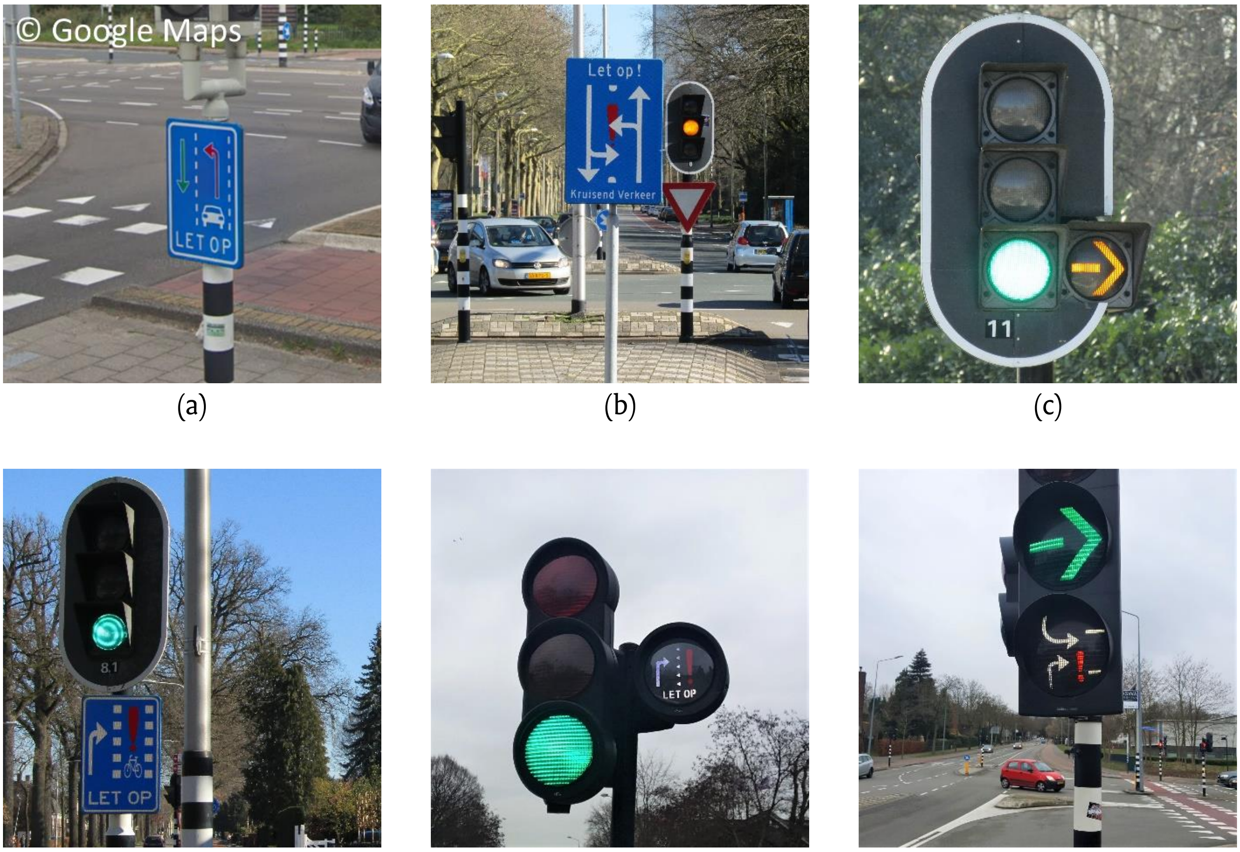
	Upchurch (1986)	Stamatiadis, Agent, & Bizakis (1997)	Davis, Moshtagh, & Hourdos (2016)	Hauer (2004)
Traffic flow volume demand of both left-turning traffic and opposing traffic	▪	▪	▪	▪
Historic crash records	▪	▪		▪
(Maximum) speeds	▪	▪	▪	▪
Sight distances	▪	▪	▪	▪
Number of lanes and other geometric design elements		▪	▪	▪
Signal display		▪		▪
Time of day			▪	

The Dutch guidelines on traffic signal controller design mention several traffic safety conditions explicitly. Only when these conditions are met, or appropriate measures are taken, permitted conflicts might be implemented. In short, the following conditions apply in the Netherlands, which are not quantified (CROW, 2006):

- Road users must be able to see each other when they have a permitted conflict to enable them to solve their conflict safely according to the priority rules;
- The speeds of the permitted conflict signal groups may not be too high;
- The road users should expect the conflict, which implies a consistent policy on permitted conflicts in the considered (urban) region, and warning signs or lights to alert road users on the permitted conflict(s), see Figure 3-1;
- The geometric road design of the intersection must enable the aforementioned conditions, in addition to being (i) small scale (no more than two lanes on the crossing approaches, see Figure 3-2a), (ii) enough space on the intersection for vehicles to wait for their turn, (iii) no blocking of the view while vehicles are waiting, and (iv) the median should not be too wide, which could also block the view, see Figure 3-2b, and Figure 3-2c;

- The traffic flow in itself should not be too large, in order to prevent overflow of a permitted conflict signal group.

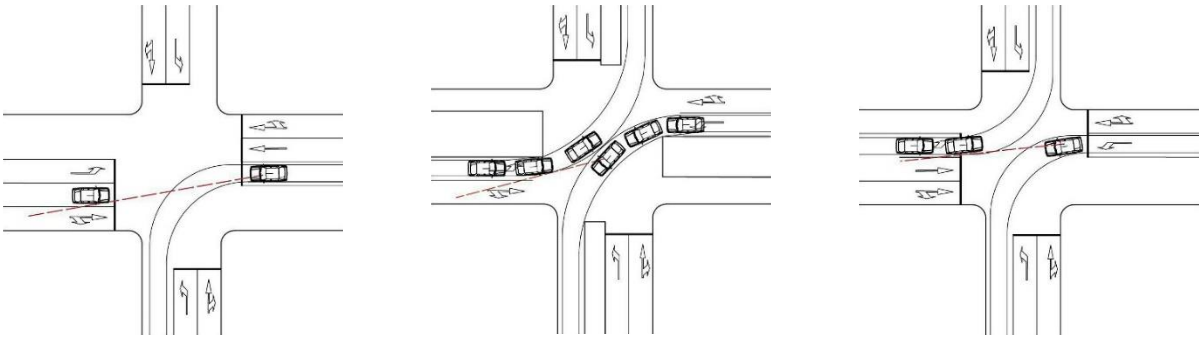
Additional measures are to be taken within the traffic signal controller itself. This relates to the two types of permitted conflicts. In the case of permitted conflicts of type 1, the green phase of the permitted conflicting signal groups have to start at the same time (synchronised start). This way, the vehicles start driving at the same moment, which emphasises the fact that the conflicting signal group has green as well. Without a synchronised start, vehicles on one of the signal groups might think that the other signal group has red, and thus assume that they have priority, while this might not be the case (CROW, 2006). This implies that, in the Netherlands, permitted conflict type 3, based on type 1, is not allowed. The same goes for Sweden, where the guidelines state explicitly that permitted conflict type 3 is not allowed (Nordlinder, Andersson, & Kronborg, 2017). When considering permitted conflicts type 2, the active mode signal group has to receive green before the car signal group (pre-start). With this pre-start, the pedestrians and/or bicyclists are already on the conflict zone before the cars, which makes clear that they have green at the same moment. Also, this gives cars the chance to see the green light of the active mode signal group and thus anticipate on crossing pedestrians and/or bicyclists. However, this pre-start demand might also be translated into a synchronised start, as long as pedestrians and/or bicyclists are on the conflict zone before the cars arrive there (CROW, 2006). In turn, this does not explicitly prohibit the implementation of permitted conflict types 3 and 4, based on type 2.



(a) (b) (c)

(d) (e) (f)

Figure 3-1 | Examples of warning signs and lights in the Netherlands to alert drivers on permitted conflicts: permitted conflict type 1 in (a) and (b); permitted conflict type 2 in (c), (d), and (e); and both permitted conflict types 1 and 2 in (f).



(a) (b) (c)

Figure 3-2 | Examples of sight lines for permitted conflict type 1: in (a) and (b), the sight of left-turning traffic might be blocked, due to (a) more than one opposing lane, and (b) a too wide median. In (c), the opposing left-turn bays lay directly opposed to each other, resulting in sufficient sight lines for left-turning traffic on the opposing through-traffic (CROW, 2006).

3.3. Traffic flow efficiency

The studies on traffic flow efficiency consequences are more scarce than traffic safety consequence studies. However, some studies have been performed, or mention general traffic flow efficiency effects. Indeed, the traffic safety study of Upchurch (1986) also found that the delay for through-going traffic increases when changing the left-turn phase from type 1, to type 3, and even more when changing it to a protected conflict, thereby excluding the effect of the length of the left-turning bay (dedicated lane for left-turning traffic). Moreover, he found that the delay depends on the product of opposing through going traffic flow volume, and the volume of left-turning traffic. Stamatiadis, Agent, & Bizakis (1997) found similar results: the higher the opposing traffic flow volume, the higher the left-turn delay becomes. Still, the left-turn delay in a protected phase is at least twice as high with respect to a permissive phase. Based on the relation between left-turn traffic flow volume, and opposing traffic flow volume in terms of delay, Al-Kaisy & Stewart (2001) derived numerical models to express the left-turn flow rate. However, they stated that the latter depends on more parameters besides the traffic flow volumes. The study of Shebeeb (1995) identified the traffic flow efficiency consequences too, besides the traffic safety effects, and found similar results as Upchurch (1986): type 1 is the most efficient left-turn conflict type, followed by types 3 and 4. Protected conflicts are least efficient. The results of the aforementioned studies are part of the literature study of Hauer (2004), as well as other studies, who found similar results in terms of traffic flow efficiency. Furthermore, the aforementioned studies based their conclusions on observation data from different states in the U.S.A.

In the traffic safety study of Dreesen (2005), she found that permitted conflicts affect the delay on signalised intersections as well, based on a literature study including some of the aforementioned studies. However, she stated that other factors affect the delay as well. Indeed, when changing the conflicts from permitted conflicts into protected conflicts, the expected growth of delay might be tempered by adjusting other parameters in the traffic signal controller as well, for instance by optimising the control program. Therefore, she stated that the found results cannot be copied one-on-one on the Belgian situation, without including those additional measures, although it remains rather likely that delays will increase when changing permitted conflicts into permitted conflicts.

Yin, Zhang, & Wang (2010) developed analytical models to estimate the capacity, and impact of blockage caused by permitted conflicts for left-turning traffic, under high traffic flow demands. They based their model on the residual queues, and left-turn capacity. They found that the length of the left-turn bay strongly affects the capacity, and the probability of blockage for permissive left-turn phasing. In a similar way, Zhou & Zhuang (2012) investigated the same, though for intersections without exclusive left-turn bays. They concluded that permissive left-turn phasing reduces the delay with respect to protected left-turn phasing, and that the profit depends on the waiting area for left-turning on the intersection – if the waiting area is sufficient, through traffic does not experience delays. Comparable results were found by Li & Sun (2016), when assessing their cellular automata model. In a similar way, Yang, Shi, Yu, & Zhou (2018) proposed an analytical model to evaluate the effect of permitted conflicts types 1 and 3 with respect to protected conflicts, in terms of delays, fuel consumption, and traffic safety. They found that these aspects depend on multiple variables, including left-turn traffic flow volume, and opposing traffic flow volume. Using their model, they concluded that permitted conflicts reduce delays, and fuel consumption, though resulting in higher traffic safety risks, measured as green time sharing ratio (ratio of effective permissive green phase, and actual green time; for small ratios, overflow queues are likely to occur).

Lastly, the traffic flow efficiency of hook-turn permitted conflicts is investigated by Currie & Reynolds (2011), who found that hook-turns result in a reduced delay, for both public transport (PT) and car traffic. This is partly related to drivers avoiding hook-turns. Furthermore, they suggest that the delay reductions could be larger in dense tram networks.

3.4. Main findings

The literature review on the known consequences of permitted conflicts, resulted in the following main findings:

- Although quite a lot of research has been done on permitted conflicts, these studies mostly focus on the traffic safety impacts, rather than traffic signal control design, and/or traffic flow efficiency effects.
- Regarding the traffic signal controller design, it is best known that the implementation of permitted conflicts result in a shorter cycle time. Besides, for a safe implementation, a separate turning bay is recommended.
- Most studies on the traffic safety implications of permitted conflicts, focused mainly on permitted conflict type 1, for this is the most common one in the U.S.A., where most studies are performed. It is concluded that the implementation of permitted conflicts results in a higher crash risk, and thus that protected conflicts result in a safer signalised intersection.
- The national guidelines provide traffic safety conditions, and countermeasures, to reduce the aforementioned increased crash risk at signalised intersections with permitted conflicts. These conditions, in particular those given in the Dutch guidelines, mention (i) visibility of road users and sight distances, (ii) speed limits, (iii) expectation management, (iv) geometric intersection design in terms of medians, etc., and (iv) traffic flow volumes. Additionally, using a pre-start, or warning signs, road users are warned on the permitted conflict.
- In several studies, it is noted that the cycle time affects the delay: the longer the cycle time, the higher the delay. However, this is not necessarily the case, since the delays also relate to the internal lost time with respect to the cycle time, although this is neither considered nor mentioned in those studies. Nonetheless, the reduced delays are concluded to come at the cost of traffic safety, as explicitly stated by multiple studies.
- At signalised intersections with permitted conflicts, in most cases types 1, 3, and 4 (left-turning traffic), the delays of both the left-turning traffic, and through-going traffic depend on the traffic flow volumes of these movements. The same goes for queue lengths, and stops. In general, it is found that signalised intersections with protected conflicts have higher delays.

4. Expected traffic flow efficiency effects of permitted conflicts

The literature review in the previous chapter gives insight in the consequences of permitted conflicts versus protected conflicts. Based on these insights, the corresponding conditions, and hypotheses relevant for this research are formulated, which describe the expected traffic flow efficiency effects of permitted conflicts. The conditions relate to the different traffic signal control design elements, and traffic safety conditions, based on the conclusions of the known consequences on traffic signal control design, and traffic safety, as found in the literature review. These conditions are used in the remainder of this research as boundary conditions that have to considered when designing a synthetic signalised intersection, whereas first the traffic signal control design elements are discussed, followed by the traffic safety conditions. The hypotheses describe how the use of permitted conflicts are expected to affect the traffic flow efficiency. Thereto, the relevant performance indicators, which relate to the hypotheses, are discussed first. The hypotheses are based on the relevant known consequences with respect to the traffic flow efficiency, as found in literature. Lastly, the chapter is summarised by discussing its main findings.

Additionally, for reference purposes, the variables, introduced in this section, are defined in *Notation and definitions* on pages ix, and x of this thesis as well.

4.1. Traffic signal control design elements

Although not much attention is given to the traffic signal control design phasing elements regarding permissive in literature, some elements are mentioned that are considered in this research. Some of these traffic signal control design elements are derived from the traffic safety conditions as given by CROW (2006). The following traffic signal control design elements are considered in the remainder of this research:

- Lane configuration: in the case of a protected left-turn phase, it is preferred to assign a dedicated left-turn bay for this signal group (Gibby, Washington, & Ferrara, 1991);
- Cycle time: the cycle time is a rather basic traffic signal control design element, which is affected by permitted conflicts as well. The implementation of protected conflicts lengthens the cycle time with respect to the implementation of permitted conflicts;
- Saturation flow: another rather basic traffic signal control design element, is the saturation flow, which is a measure for capacity during green time. Due to permitted conflicts, traffic on a signal group (a) might have to wait, and yield to crossing traffic on signal group (b), thereby reducing the capacity of signal group (a), and thus the saturation flow. Then, a lower saturation flow will result in a longer cycle time, implying that the implementation of protected conflicts also reduces the cycle time in a certain way, and thus that there are multiple factors that affect the cycle time;
- A synchronised start of the permitted conflicting signal groups is to be applied in the case of permitted conflicts of type 1 (CROW, 2006). Given this condition, permitted conflict types 3, based on type 1, are not allowed;
- A pre-start of the permitted conflicting signal groups is to be applied in the case of permitted conflicts of type 2, whereas it holds that the minimum pre-start time $t_{\text{ps,min}} \geq 0$ s (CROW, 2006).

4.2. Traffic safety conditions

In the discussed guidelines, several traffic safety conditions are mentioned that have to be implemented to ensure a safe implementation of permitted conflicts. Given the scope of this research (the Netherlands), the Dutch guidelines are leading in terms of traffic safety conditions for permitted conflicts. In short, this comes down to the relevant following traffic safety conditions for this research (CROW, 2006):

- Road users must be able to see each other when they have a permitted conflict to enable them to solve their conflict safely according to the priority rules;
- The speeds of the permitted conflict signal groups may not be too high. This implies urban speeds, with maximum speeds ≤ 50 km/h;
- The geometric road design of the intersection must enable the aforementioned conditions, in addition to being (i) small scale (no more than two dedicated lanes on the crossing roads), (ii) enough space on the intersection for vehicles to wait for their turn, (iii) no blocking of the view while vehicles are waiting, and (iv) the median should not be too wide, which could also block the view, see Figure 3-2;
- The traffic flow in itself should not be too large, in order to prevent overflow of a permitted conflict signal group that has to yield for another signal group. In literature, this is not quantified, although this is solved by assigning "sufficient green time" to a signal group. That is, the green time should be long enough to prevent overflow, while also taking into account the delay of other conflicting signal groups. However, this is not quantified.

Given the aforementioned traffic safety conditions, only permitted conflict types 1 and 2 are considered in this research. Although permitted conflict type 4 is allowed, it is only an implicit part of this research, since this permitted conflict type is considered the result of a vehicle-actuated traffic signal controller, rather than an explicit standard setting. Furthermore, permitted conflict type 5 (hook-turns) are not included in the remainder of this research, given the limited implementation in practice, at least for motorised traffic. This implies that the scope of this research is narrowed down to only permitted conflicts of types 1 and 2.

4.3. Traffic flow efficiency performance indicators

The traffic flow efficiency hypotheses are based on the findings in the literature review. However, in literature, the focus is mainly on traffic flow volumes, and delays, which is a rather narrow view of the traffic flow efficiency performance indicators. Indeed, the traffic flow efficiency can be described by various other variables as well, e.g. cycle times, degree of saturation, stops, and queue lengths (AWV, 2009; AWV, 2011; CROW, 2006; FGSV, 2010; Koonce, et al., 2008; TRB, 2000; TRB, 2012; Vägverket & Svenska Kommunförbundet, 2004). Therefore, the relevant performance indicators are first discussed. Based on the findings from the literature review, and the relevant performance indicators, several hypotheses are formulated.

The relevant performance indicators are discussed per assessment aspect. The three assessment aspects are mentioned in section 1.4, and describe the three main aspects related to the traffic flow efficiency elements. In short, the following three aspects are considered:

1. *Throughput and capacity*: the traffic flow efficiency expressed as number of vehicles per time step;
2. *Queues*: the traffic flow efficiency expressed in terms of congestion (slow driving traffic to standstill);
3. *Travel times and delays*: traffic flow efficiency expressed in temporally quantities.

4.3.1. Throughput and capacity

The *Throughput and capacity* assessment aspect includes the performance indicators intersection capacity, load ratio, and degree of saturation. These three performance indicators are related to each other, since the intersection capacity relates to the load ratio, and the load ratio relates to the degree of saturation.

In the case of the degree of saturation, the effective green time $T_{G,\text{eff}}$ [s] is an important variable. The effective green time denotes the time that traffic is being served, thereby excluding the start-up lost time (start lag λ_1 [s]), and including that part of the amber phase in which traffic is still passing the stop line (end lag λ_2 [s], also known as utilised amber time), as visualised in Figure 4-1. In mathematical terms, this comes down to:

$$T_{G,\text{eff}} = T_G - \lambda_1 + \lambda_2 \tag{4-1}$$

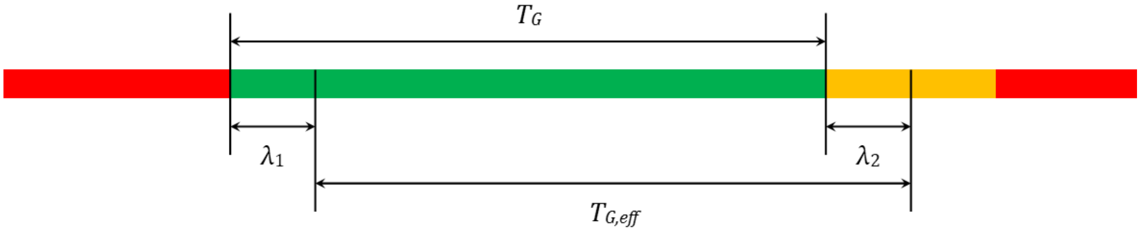


Figure 4-1 | Green time and effective green time.

In the Dutch guidelines, it is mentioned that the green time start lag λ_1 depends on the movements involved at a signal group: for through-going signal groups, $\lambda_1 = 3$ s, while for turning signal groups $\lambda_1 = 5$ s, at most (Grontmij, 2001). For simplicity, it assumed that $\lambda_1 = 3$ s for all signal groups. Also, from the Dutch guidelines, the setting for the green time end lag λ_2, in Dutch literature also known as utilised amber time, can be derived. In general it holds that $\lambda_2 = 3$ s (CROW, 2006). That way, it holds that, in fact:

$$\lambda_1 = \lambda_2 \tag{4-2}$$

and thus that:

$$T_{G,\text{eff}} = T_G \tag{4-3}$$

The intersection capacity is based on the saturation flow. As stated, it is known that the saturation flow of a permitted conflict signal group that has to yield to another signal group, decreases due to the implementation of said permitted conflict. This is caused by the fact that traffic might have to wait, thereby reducing the throughput during the green time of such a signal group. In turn, this means that, for an equal flow, the load ratio y [-], given as:

$$y = \frac{q}{s} \tag{4-4}$$

with traffic flow volume q [pce/h], and saturation flow s [pce/h], will increase due to the reduced saturation flow. Because the load ratio is a measure for how much vehicles a signal group can serve, given its saturation flow, it means that with an increased load ratio, the capacity of that signal group is reached sooner. This also introduced the other performance indicator, namely the load ratio.

Lastly, the degree of saturation x [-] denotes the ratio of the load ratio y, and u [-], denoting the fraction of effective green time per cycle $u = T_{G,\text{eff}}/T_C$ with cycle time T_C [s], and effective green time $T_{G,\text{eff}}$ [s]:

$$x = \frac{y}{u} = \frac{qT_C}{sT_{G,\text{eff}}} \tag{4-5}$$

Here, it also holds that a decreased saturation flow results in an increased degree of saturation. The higher the degree of saturation is, the more likely it is that congestion occurs. Indeed, for a degree of saturation $x \geq 1$ of a signal group, it holds that the signal group is oversaturated, and thus that not all vehicles can be served during the green phase. The result is the build-up of a (overflow) queue, and potentially spillback. Also, it increases the number of stops, see also section 4.3.2.

4.3.2. Queues

The assessment aspect *Queues* relates the congestion caused by the traffic signal controller. This is expressed using the performance indicators (i) queue lengths L [m], and (ii) number of stops h [#], since these performance indicators describe (i) the length of the queue, and (ii) how the queue is dissolved. The latter means that more stops imply oversaturation, and thus inability to completely serve the queue during the green phase of that signal group, as introduced in the previous section.

4.3.3. Travel times and delays

The assessment aspect of *Travel times and delays* include the performance indicators (i) cycle time T_C [s], and (ii) delays d [s/pce].

The cycle time is based on the intersection load ratio Y [-], given as:

$$Y = \sum_i y_i \qquad \forall i \in K \tag{4-6}$$

and the internal lost time T_L [s]:

$$T_L = \sum \left(\lambda_1 + t_{\text{clear},i,j} + (T_A - \lambda_2)\right) \qquad \forall i,j \in K \tag{4-7}$$

with signal groups i, and j, the set of signal groups K [-] of signal groups in the critical conflict group, green time lags λ_1 [s] and λ_2 [s], amber time T_A [s], and clearance time $t_{\text{clear},i,j}$ [s] from signal group i to j. Together with scaling parameters θ [-], and ϕ [-], the cycle time is mathematically defined as:

$$T_C = \frac{\theta T_L + \phi}{1 - Y} \tag{4-8}$$

The scaling parameters are used to distinguish the minimum cycle time, and optimal cycle time. For the minimum cycle time, it holds that $\theta = 1$ and $\phi = 0$. The optimal cycle time in the Netherlands is computed with $\theta = 1.5$ and $\phi = 5$, as found by Webster (1958), which are most used in the Netherlands, as stated by CROW (2006). The other variables – intersection load ratio, and internal lost time – depend on the intersection characteristics, and the selected block sequence. That is, for a random signalised intersection, the intersection load ratio, and internal lost time of block sequence (a) might differ from block sequence (b). Regardless, it holds in general that the more blocks are considered, the longer the minimum, and optimal cycle time becomes.

Regarding (ii) delays, an important distinction is to be made, namely between delay on the one hand, and stop delay on the other hand. The stop delay denotes the waiting time – the delay a vehicle experiences due to standing still (Dutch: *wachttijd*) –, whereas the delay includes stop delay, acceleration delay, and deceleration delay (Dutch: *verliestijd*), see Figure 4-2, and appendix A. In this research, only delay is considered.

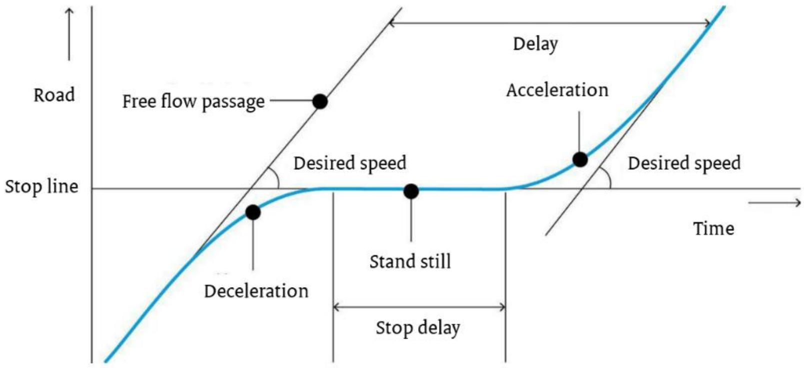


Figure 4-2 | Delay, deceleration delay, stop delay, and acceleration delay (CROW, 2006).

4.3.4. Overview

In short, the following performance indicators are considered in this research:

1. *Throughput and capacity*:
   - (Intersection) capacity, based on saturation flow;
   - Load ratio;
   - Degree of saturation;
2. *Queues*:
   - Queue length;
   - Stops;
3. *Travel times and delays*:
   - Cycle time;
   - Delay.

4.4. Hypotheses

The objective of this research is to present the effects of permitted conflicts on the traffic flow efficiency with respect to protected conflicts. Therefore, the hypotheses are formulated from this point of view: what are the expected effects? The hypotheses include the aforementioned performance indicators. The hypotheses are formulated as expected effects. In short, the following hypotheses are formulated, per assessment aspect (i) throughput and capacity, (ii) queues, and (iii) travel times and delays.

4.4.1. Throughput and capacity

The use of permitted conflicts is expected to improve the throughput, and capacity of a signalised intersection. The hypothesis is that, due to permitted conflicts, the cycle time reduces, and thus that more traffic per hour can be served, thereby improving the degree of saturation, that is, lowering the degree of saturation. Also, when more traffic per hour is served, the throughput of the intersection increases as well. However, the reduction of the cycle time, and thus decrease of degree of saturation, is expected to be limited due to a reduced saturation flow. A reduced saturation flow might result in a lower intersection capacity when permitted conflicts are implemented. Nonetheless, it is expected that the overall effect is positive regarding the implementation of permitted conflicts. In the same way, it is expected that the intersection load ratio will increase, because more traffic is being served. Also, for some signal groups, it is expected that the saturation flow reduces, thereby further increasing the load ratio.

On the other hand, it is expected that the degree of saturation will decrease. This expected to be caused by reduction of the cycle time. That is, the effect of the increased load ratio is expected to be counterbalanced by the reduced cycle time. This expected to be the result of the hypothesis that less blocks are needed in the block sequence when permitted conflicts are implemented. Although it is also expected that the green time will reduce as well, it is expected that the green time is not reduced as much as the cycle time. The improved fraction of effective green time per cycle per signal group is then expected to limit the increase of the degree of saturation.

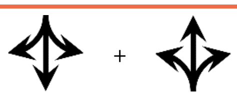
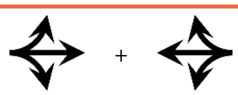
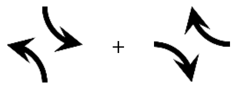
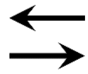
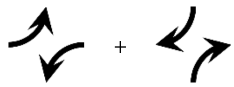
4.4.2. Queues

The implementation of permitted conflicts is expected to reduce the queue lengths, as a consequence of the reduced cycle time. In a similar way, it is expected that the number of stops will decrease as well, though only for the signal groups without a permitted conflict. For signal groups in a permitted conflict, it is expected that the number of stops do increase, due to the fact that vehicles on these signal groups have to stop, and yield to crossing traffic during their green phase. Although the effect of the increased number of stops of signal groups with permissive phasing is expected to be more severe than the reduction of the other signal groups, the reduction of the latter signal groups is expected to suppress this effect somewhat. It must be noted that it is also expected that if the same lane is used to serve right-turning, through-going, and left-turning traffic, the aforementioned effect might not be suppressed. However, as will be discussed in section 6.2.1, multiple lanes are considered.

4.4.3. Travel times and delays

In literature, it is suggested that a reduction of the cycle time results in a reduced delay as well. However, the literature did not consider, nor mention the effect of internal lost time on delays (Hauer, 2004; Stamatiadis, Agent, & Bizakis, 1997; Upchurch, 1986). The cycle time is computed using this internal lost time. The lost time relates to (i) the block sequence, and (ii) the clearance lost time. First, (i) the block sequence affects the cycle time in such a way that the cycle time is longer if more blocks are included in the block sequence. Indeed, on a conflict-free signalised intersection with four approaches, at least four blocks are needed, while the implementation of permitted conflicts might allow the use of a two-phase block sequence, comparable to the current practice in Belgium, for instance, see Table 4-1. Because there is some time lost between two consecutive blocks, the hypothesis is that if more blocks are used, more time is lost in total. Secondly, the internal lost time, and thus the cycle time, is reduced due to an exclusion of several conflicts as well, thereby explicitly reducing (ii) the clearance lost time. Indeed, with permitted conflicts, several conflicts are not controlled, thereby removing the clearance lost time for those conflicts from the computation of the internal lost time. That way, the cycle time is reduced as well. However, it must be noted that due to a reduced saturation flow, but also due to certain traffic safety measures, the reduction of cycle time might be limited. Nevertheless, it holds that reducing the number of blocks, in this case by implementing permitted conflicts, the lost time is reduced, thereby reducing the cycle time, and thus the delay as well.

Table 4-1 | Potential block sequences for a signalised intersection with four approaches, without active modes: one with permitted conflicts, resulting in a two-block-controller, and one for a conflict-free controller, resulting in a four-block-controller.

Block	I	II	III	IV
Permitted conflicts			N/A	N/A
Protected conflicts				

4.5. Main findings

The main findings of this chapter are:

- The Dutch guidelines, among others, provide a list of traffic signal control design elements in relation to traffic safety, to ensure a safe implementation of permitted conflicts. In short, these elements relate to (a) lane configuration, (b) cycle time, (c) saturation flow, and (d) a synchronised, or pre-start of signal groups with a permitted conflict.
- In relation to the aforementioned traffic signal control design elements, the following traffic safety conditions are considered, which are not yet quantified:

  i. Sight lines: road users must be able to see each other approaching, to safely negotiate the permitted conflict;
  ii. Speed limit: the speeds might not be too high, thus urban speeds of ≤50 km/h are considered;
  iii. Geometric intersection design: the intersection must be small scale (i.e. lane configuration), there must be a waiting area, there may not be blocking of the view of waiting vehicles, and the median width must be sufficient;
  iv. Traffic flow volumes: the volumes must be low enough to prevent oversaturation;
  v. A synchronised, or pre-start of signal groups must be implemented, alongside warning sings, or lights, depending on the type of permitted conflict.

- To assess the traffic flow efficiency performance of permitted conflicts with respect to protected conflicts, three assessment aspects are considered, whereas each aspect relates to a set of performance indicators:

  1. *Throughput and capacity*: (intersection) capacity (in relation to saturation flow as well), load ratio, and degree of saturation;
  2. *Queues*: queue length, and number of stops;
  3. *Travel times and delays*: cycle time, and delays.

- For each assessment aspect, hypotheses are formulated in terms of what the expected traffic flow efficiency effects are of implementing permitted conflicts when compared to implementing protected conflicts. These hypotheses are tested in chapter 6. The hypotheses are summarised as follows:

  - The (intersection) throughput improves, thus a higher (intersection) throughput is expected;
  - The saturation flow is expected to decrease. This expected to be due to traffic that now has to yield for crossing traffic, during a green phase;
  - As a consequence, it is expected that the load ratio increases;
  - The degree of saturation improves, which is defined as an expected lower degree of saturation;
  - Reduced queue lengths are expected;
  - For signal groups (with cars) in a permitted conflict that have to yield for other traffic, the number of stops is expected to increase;
  - For the other signal groups (with cars), the number of stops is expected to decrease;
  - The cycle time is expected to decrease.
  - The former relates to the number of blocks in the block sequence: it is hypothesised that the fewer blocks there are in the block sequence, the shorter the cycle time is;
  - The expected reduced cycle time, also results in less delay.

5. Analytical gap acceptance models: simulation model validation

An important part of a simulation study, is the validation of the used simulation model. In this case, this relates to how well the simulation model simulates permitted conflicts. Thereto, the gap acceptance model in VISSIM, in relation to permitted conflicts, is assessed, in terms of how well VISSIM simulates "real" gap acceptance. Moreover, it enables a better understanding of the simulated gap acceptance behaviour at the conflict zones of permitted conflicts, and thus a better understanding of the simulation results in the following chapters. This validation is done using gap acceptance models, which are analytical models used to estimate the critical gap size. The critical gap is the minimum gap size of gaps in a crossing stream for which more gaps are accepted than rejected, usually given as the gap size where the gap acceptance probability is over 50%. The assessment of gap acceptance models in relation to the simulation model helps to establish a reference window. Moreover, it is part of the validation of the simulation model, in particular with respect to the crucial investigation aspect, namely permitted conflicts. Indeed, the traffic flow efficiency effects are expected to be related to the gap acceptance models, e.g. regarding intersection capacity, and delay, as indicated by several studies (Devarasetty, Zhang, & Fitzpatrick, 2012; Kimber, 1989; Kittelson & Vandehey, 1991; Zohdy, Sadek, & Rakha, 2010).

Therefore, this chapter discusses the analytical gap acceptance models as introduction on the validation of the VISSIM simulation model. First, gap acceptance models in general are discussed in terms of how a critical gap might be modelled, and how such methods are applied in practice. Secondly, gap acceptance, and critical gap problems are discussed in the case of signalised intersections, in particular regarding permitted conflicts. Here, the different factors, such as sight obstruction, and considered traffic modes, affecting the critical gap size are discussed. Next, the VISSIM simulation model is validated in relation to the gap acceptance models: how well is VISSIM able to correctly model, and simulate the critical gaps at signalised intersections with permitted conflicts, with respect to a real-life signalised intersection with permitted conflicts? The answer on this question indicates a reference window of the VISSIM simulation model with respect to permitted conflicts, and offers a reference window for the results of the simulation study. Lastly, the chapter concludes with some general remarks on the main findings.

Additionally, for reference purposes, the variables, introduced in this section, are defined in *Notation and definitions* on pages ix, and x of this thesis as well.

5.1. Gap acceptance studies in general

Gap acceptance models are developed, and researched over many years. Therefore, multiple methods to develop such models, or estimate the critical gap are available. One of these methods is Raff's method, which uses data of accepted, and rejected gaps, of the evaluated intersection. This might be either a signalised intersection with permitted conflicts, or an uncontrolled intersection, thus with the regular priority rules in place. Then, the cumulative distributions are plotted, whereas for the rejected gaps, the inverse function is plotted. The intersection of the two functions denotes the gap size which is accepted by over half of the drivers, and thus denotes the critical gap size (Raff & Hart, 1950). Another method to estimate the critical gap size, is by deriving a probability model, or utility function, including different factors, such as distance to the next downstream intersection, speed limit, delay, median width, etc., that affect the critical gap distribution. This method is also known as the logistic regression method (Harwood, Mason, Brydia, Pietrucha, & Gittings, 1996). Based on data on accepted, and rejected gaps, the values for the scaling parameters corresponding to those factors are estimated. Then, the critical gap size is given by the minimum gap size for which the gap acceptance probability is over 50%. Both Raff's method, and the logistic regression method are used in practice, and scientific research.

The studies on gap acceptance models usually focus on the gap acceptance by traffic on a minor road that wants to turn onto, or cross a major road, thereby usually not including traffic signalisation. For instance, (Ashton, 1971) investigated several factors that are involved in the analysis of accepted gaps, and rejected gaps, such as traffic flow volume, and impatience of the driver, using Raff's method. However, (Ashton, 1971) did not consider traffic signalisation, or geometric intersection design as factors. In a similar way, (Kittelson & Vandehey, 1991) investigated the effect of delays for the front of the queue on the critical gap distribution on unsignalised intersections, in relation to the guidelines given by the Highway Capacity Manual (HCM). They found that the longer the delay of the front of the queue, the shorter the gaps that are accepted by drivers. Another application of these models, is to assess the gap acceptance with respect to the capacity of (unsignalised) intersections (Kimber, 1989).

5.2. Gap acceptance problems at signalised intersections

However, there are studies performed in relation to gap acceptance of turning traffic with an opposing through-going stream. These studies also included signalised intersections.

5.2.1. Critical gaps for left-turning traffic

Zohdy, Sadek, & Rakha (2010) investigated the gap acceptance behaviour with respect to delay, weather conditions, and travel time to the conflict zone, using a logistic regression model, for permissive phasing of left-turning traffic (permitted conflict type 1). The signalised intersection they used, however, had two opposing through-going lanes, which was also a factor in the gap time distribution, since the results identified two critical gap distributions: one for the first lane, and one for the second lane, whereas the former was found to be lower than the latter. The range depended on the used model. For the first lane, the critical gap was found to be approximately 6.0 to 7.2 seconds. The awareness of drivers regarding gap acceptance in permitted conflicts on signalised intersections, is reviewed by Mao, et al. (2018), using a logistic regression model. They concluded that the estimated critical gap size for a safe left-turning movement in a permitted conflict with a through-going stream is approximately 4.0 seconds.

5.2.2. Effect of sight-obstruction

Besides the general critical gap studies, some studies focused in particular on the effect of sight distances, and sight-obstruction at signalised intersection, in relation to gap acceptance, and permitted conflict type 1. Using logistic regression, Yan & Radwan (2008) found that the median width, which relates to sight-obstruction as in Figure 3-2, does affect the critical gap size. Their logistic regression model is based on data of a signalised intersection with a median width of approximately 6.1 metres, for which it was found that without sight-obstruction – no opposing left-turning vehicle blocking the view on opposing through-going vehicles – the critical gap is with 5.6 seconds close to the recommended value of 5.5 seconds in the guidelines of AASHTO (2001). However, in the case of sight-obstruction, the critical gap increased to 7.7 seconds. Moreover, the opposing through-traffic flow volume also affected the critical gap size: the higher the volume, the longer the critical gap. All together, they concluded that sight-obstruction, and high traffic flow volumes of opposing through-going traffic increase the critical gap, and thus increase delays and reduce the capacity of the intersection. Similar results were found by Devarasetty, Zhang, & Fitzpatrick (2012), who also included the stop delay of the front of the queue, and time needed to cross the opposing lane(s), among others. They found a critical gap ranging from 5.0 to 6.8 seconds, using their logistic regression model. Lastly, also Ogallo & Jha (2014) found, with Raff's method, that with sight-obstruction, the critical gap is approximately 5.4 seconds, versus 5.0 seconds without sight-obstruction, thereby reducing the capacity of the intersection.

5.2.3. Permitted conflicts with active modes

Guo, Zhang, & Rong (2012) developed a model to study the reduction of the saturation flow of turning movements with a permitted conflict with parallel, through-going bicycle streams. In their model, they included the effect gap acceptance had. Although they did not mention the critical gap distribution, they found comparable results as the aforementioned studies, namely that permissive phasing reduces the saturation flow of turning movements. On the other hand, Alhajyaseen, Asano, & Nakamura (2013) investigated the traffic safety implications of permitted conflict type 2 on pedestrians in particular, also in relation to gap acceptance. They found that the point where pedestrians started to cross the approach – coming from the same origin as the turning car traffic (near-side), or in the opposite direction (far-side) – affects the critical gap size. Indeed, they found that in the case of near-side pedestrians, the critical gaps are shorter than for far-side pedestrians, and bi-directional pedestrians, namely approximately 4.6 seconds, 6.9 seconds, and 7.0 seconds, respectively. This implies that drivers might have different strategies on gap acceptance, depending on the direction of pedestrians. This is also illustrated with the speeds of drivers: the speeds of vehicles are lower with bi-directional pedestrians. They did not investigate the relation between speed and clearance times.

5.2.4. Permitted conflict model frameworks

Lastly, some studies were done in which gap acceptance models are incorporated. For instance, Beard & Ziliaskopoulos (2006) formulated a framework for traffic signal optimisation. In their framework, they included constraints related to permitted conflict type 1. Their constraints related to how permissive phasing affects the traffic flow volume, and the critical gap size, which they set to 6.0 seconds, according to TRB (2000). Another study by Zohdy & Rakha (2012), including the same signalised intersections as Zohdy, Sadek, & Rakha (2010), and Yan & Radwan (2008), developed a gap acceptance behaviour model for permitted conflict type 1. They based their framework on the logistic regression model of Zohdy, Sadek, & Rakha (2010), thereby including the factors delay, weather conditions, and travel time to the conflict zone. In their framework, they specified critical gap values based on the weather conditions, and considered conflict point, thereby ranging from 3.9 seconds to 4.1 seconds in dry conditions, and from 5.5 seconds to 5.9 seconds in wet conditions.

5.2.5. Conclusion

Overall, the conclusion regarding gap acceptance models is that the critical gap size depends on multiple factors, including sight-obstruction, front-of-queue delay, and travel time to the conflict zone. In the case of gap acceptance with respect to active mode streams, the direction of the active mode is relevant as well. In short, the critical gap size increases when:

- There is sight-obstruction, thus the wider the median, the larger the critical gap;
- The front-of-queue delay is low. In other words, drivers tend to become more impatient when waiting for a gap, and thus accept shorter gaps if they are waiting for a longer period of time;
- Pedestrians, or active modes in general, are oncoming traffic, thus when active modes start crossing a road from the far-side, or when there is bi-directional active mode traffic.

Another conclusion is the seemingly contradicting results of these gap acceptance studies with respect to the known consequences of permitted conflicts, as discussed in chapter 3. In studies on permitted conflicts in general, it was found, or hypothesised that permitted conflicts improve the intersection throughput, and capacity, hence the hypothesis on improved intersection capacity, as formulated in section 4.4.1. However, the gap acceptance studies found that the opposite might be the case. Indeed, several studies emphasise the aforementioned hypothesis that the saturation flow reduces due to permitted conflicts. Consequently, this affects the gap acceptance behaviour of drivers as well. Nevertheless, it is assumed that the reduction of the saturation flow is one of many more factors affecting the cycle time, and thus that the cycle time might decrease nonetheless, just as hypothesised in section 4.4. Therefore, it is concluded that the aforementioned expected decrease of the cycle time is less due to the lower saturation flow.

Lastly, in short, the rage of critical gap sizes in literature, as found in this section, is summarised in Table 5-1. In this table, the critical gap sizes are listed per reference, including the corresponding research objective, and general remarks regarding the reference.

Table 5-1 | Critical gap size in literature.

Reference	Research subject	Critical gap size [s]	Remarks
AASHTO (2001)	Geometric road design guideline	5.5 (passenger car)	One critical gap size regardless geometric intersection design; critical gap size varies per vehicle class
Devarasetty, Zhang, & Fitzpatrick (2012)	Effect of sight-obstruction on critical gap size	5.0 – 6.8	Logistic regression using data from multiple intersections; critical gap size estimated using different data sets
Mao, et al. (2018)	Critical gap permitted conflict type 1	4.0	Logistic regression using data from one intersection
Ogallo & Jha (2014)	Effect of sight-obstruction on critical gap size	5.0 (no sight-obstruction) 5.4 (sight-obstruction)	Raff's method using data from multiple intersections
TRB (2000)	Geometric road design guideline	4.5 (critical gap permitted left turn) 4.1 (base critical gap)	The base critical gap size is part of a formula to estimate the critical gap size of movement
Yan & Radwan (2008)	Effect of sight-obstruction on critical gap size	5.6 (no sight-obstruction) 7.7 (sight-obstruction)	Logistic regression using data from one intersection
Zohdy, Sadek, & Rakha (2010)	Effect of stop delay, and weather conditions on critical gap size	6.0 – 7.2 (left lane, P1) 8.1 – 9.2 (right lane, P2)	Logistic regression using data from one intersection; critical gap size estimated using different regression models

5.3. Gap acceptance in VISSIM

The validation of the VISSIM simulation model regarding gap acceptance, and permitted conflicts at signalised intersections, focuses on how well VISSIM is able to model this gap acceptance problem at signalised intersections. Therefore, a separate pilot VISSIM model is built, based on the research by Zohdy, Sadek, & Rakha (2010), and Zohdy & Rakha (2012). More precisely, the intersection they investigated is modelled. Then, the critical gap results from VISSIM are compared with their research results, thereby including other researches as well. The deviation of the critical gap size in VISSIM with respect to the research results is then assumed to be a measure for how well VISSIM models this problem.

5.3.1. Intersection data

The validation of the VISSIM simulation model is done by simulating the signalised intersection investigated by Zohdy, Sadek, & Rakha (2010), and Zohdy & Rakha (2012). This is the signalised intersection of North Franklin Street (Business Route 460), and Depot Street in Christiansburg, Virginia, U.S.A.

5.3.1.1. Intersection characteristics

The signalised intersection in Christiansburg, Virginia, U.S.A., has four approaches that cross each other at an approximate 90° angle. The eastern, and northern approaches – respectively North Franklin Street east, and Depot Street north – both have two lanes approaching the intersection, the southern approach – Depot Street south – has three lanes, and the western approach – North Franklin Street west – has four lanes. All exits of the intersection have two lanes, except for the northern exit (Depot Street north), which has only one lane.

Furthermore, the maximum speed on the eastern, and northern approaches is 40 kilometres per hour (25 miles per hour), and on the western, and southern approaches 55 kilometres per hour (35 miles per hour). Parallel to North Franklin street, a pedestrian crossing on the southern approach is present. However, this is not included in the simulation model, see Figure 5-1, as this was not included in the research of Zohdy, Sadek, & Rakha (2010) as well.

Figure 5-1 | Satellite image (left; Google Maps, 2018), and corresponding VISSIM model (right) of the signalised intersection in Christiansburg, Virginia, U.S.A., with maximum speeds in kilometres per hour (Zohdy, Sadek, & Rakha, 2010).

5.3.1.2. Traffic flow volumes

The traffic flow volume on the intersection is given by Zohdy, Sadek, & Rakha (2010), and is found to be 26,671 vehicles per day. However, it is not stated what the traffic flow volume per hour is, for instance during a peak hour, and what the origin-destination (OD) traffic flow volumes are. Therefore, assumptions are made on both aspects. Although the effect of different assumptions are not investigated in this research, due to the limited time available, it is assumed that this does only affect the number of gaps that are offered, and thus does not affect the outcomes in terms of accepted gap size, and rejected gap size.

First, it is assumed that the peak hour traffic flow volume is 9% of the daily traffic flow volume. This is according to the found traffic flow distribution as given in CROW (2012). Secondly, given the geometric intersection design, in particular regarding the lane configuration, it is assumed that the south-west movement and vice versa are the most prominent movements, and should therefore have the highest traffic flow volume. The east-west and vice versa movements, and south-east and vice versa movements are the second- and third-prominent movements. Movements to, and from the northern approach are assumed to have the lowest traffic flow volume. That way, the OD-matrix as given in Table 5-2 is constructed.

Table 5-2 | Constructed, assumed OD-matrix, given in vehicles per hour.

Destination → Origin ↓	North Franklin Street (east)	Depot Street (south)	North Franklin Street (west)	Depot Street (north)
North Franklin Street (east)	0	215	348	36
Depot Street (south)	311	0	472	57
North Franklin Street (west)	253	560	0	27
Depot Street (north)	36	64	20	0

5.3.1.3. Traffic signal controller settings

The traffic signal control settings are mostly assumed as well, since Zohdy, Sadek, & Rakha (2010) only gave the block sequence, as shown in Figure 5-2. They stated explicitly that permissive phasing is included regarding the left-turning traffic from North Franklin Street to Depot Street.

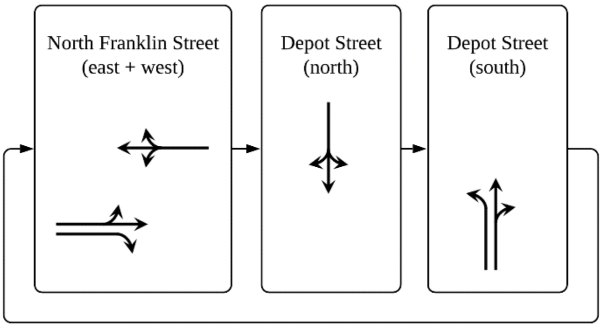


Figure 5-2 | Block sequence, as given by Zohdy, Sadek, & Rakha (2010).

As stated above, the other traffic signal control settings are not given in the paper of Zohdy, Sadek, & Rakha (2010), thus it is not known whether the signalised intersection in practice is controlled with a fixed time controller, or a vehicle-actuated controller. Therefore, it is assumed that a fixed time controller is applied. Other aspects (e.g. cycle time*, green times*, etc.) of the traffic signal controller are assumed as well, given the limited time for this research, in particularly with respect to the research objective – the objective of this research is not to assess the performance of VISSIM regarding permitted conflicts in-depth. These assumed settings are not corresponding to the optimal settings that would have followed from a thorough traffic signal control development, e.g. using COCON (a (fixed time) traffic signal control design tool, commonly used in the Netherlands, see also appendix A). However, as stated, given the limited time, this is assumed to be irrelevant for the validation of the VISSIM simulation model in general regarding the modelling of permitted conflicts. Indeed, the objective of this particular simulation is to validate the VISSIM simulation model on how it models permitted conflicts in relation to gap acceptance.

5.3.2. Gap acceptance settings

The validation of the VISSIM simulation model is done for three alternatives on the same intersection. The alternatives denote different settings for gap acceptance in VISSIM. Thereto, the conflict zones are simulated using *Conflict Areas*, for which different settings could be applied regarding the front gap, and rear gap. The front, and rear gap both describe the minimum time interval between the rear-end of vehicle leaving the *Conflict Area*, and the front of another, conflicting vehicle entering the *Conflict Area*. The default settings are considered as the base case alternative, with a front, and rear gap setting of 0.50 seconds. A longer setting for these gaps, for instance, will result in a larger critical gap size. Then, the different alternatives, and corresponding settings for the front, and rear gap are given in Table 5-3.

Table 5-3 | Alternatives and corresponding settings.

Alternative	Front gap [s]	Rear gap [s]
0. Default gap settings (base case)	0.50	0.50
1. Decreased gap settings	0.25	0.25
2. Increased gap settings	0.75	0.75

* The cycle time, green times, etc. are considered as assumed cycle time, green times, etc., because they are based on assumed traffic flow volumes.

Another relevant setting relates to blockage: *AvoidBlock*. If this setting is set on 100%, all vehicles on the *Conflict Area* will avoid standing still on the *Conflict Area*, and thus avoid blockage. The default setting is 100%. This default setting is used as well, and is not adjusted as a way to define alternatives, because it is assumed that this default setting represents reality rather well, since rivers tend to prevent standing still on the conflict zone as well, given undersaturated conditions. During oversaturation, and potentially spillback from a downstream intersection, drivers might stand still on the conflict zone, and thus block the *Conflict Area*. However, since a single, isolated signalised intersection is simulated, this spillback is not relevant, and thus it is assumed that a different *AvoidBlock* setting is irrelevant as well.

5.3.3. Simulation model settings

5.3.3.1. Simulation period

Each run of the simulation consists of 4200 simulation seconds (70 simulation minutes). In the data collection, and data analysis, only the middle hour is used, thus the first, and last 300 simulation seconds (5 simulation minutes, cumulative 10 simulation minutes) are not included. This means that data is collected, and analysed for a simulation period of 3600 seconds (60 simulation minutes). That way, the data is analysed in the period when the signalised intersection is fully functional. Indeed, during the first 300 simulation seconds, the network is assumed to be filling itself, which might cause disturbances in the data. The emptying of the network might also cause disturbance, hence the removal of the last 300 simulation seconds from the analysis. Moreover, this way, the data is already scaled to values per hour.

5.3.3.2. Number of runs

The number of runs used for the validation of the VISSIM simulation model is 10. In other words, the model is validated using data from 10 runs per alternative. Using equations (6-1) to (6-3), as will be discussed in section 6.2.3, it is found that this is sufficient to ensure a 95% reliability, based on the gap size of all offered gaps of five pilot runs, and an accepted standard deviation of 22.5 seconds of all offered gaps – thus both accepted, and rejected gaps together – for an average of 20.2 seconds.

5.3.3.3. Speeds, acceleration, and deceleration settings

The speeds are set according to the maximum speeds that are in force on the four approaches. Thereto, new speed distributions are constructed representing the maximum speed. The speed distribution accept some deviation of the maximum speed, namely 2.5 kilometres per hour. Then, the used speed distributions are 40 ± 2.5 kilometres per hour, and 55 ± 2.5 kilometres per hour. At the curves, the speeds are lower, using *Reduced Speed Areas*: right-turning curves have a speed setting of 20 kilometres per hour, and left-turning curves 25 kilometres per hour. Regarding the settings for the acceleration, and deceleration, the default settings in VISSIM are used.

5.3.4. Data collection method

The data on accepted, and rejected gaps is collected using *Data Collection Points* in VISSIM. These points are used (i) to detect a left-turning vehicle waiting for an appropriate gap, and (ii) to measure the gaps in the through-going traffic flow. For both cases, raw data from the *Data Collection Points* is used. Then, (i) is found by measuring the occupancy of a *Data Collection Point* for left-turning traffic 1 metre before the conflict zone. (ii) The gap size is determined by measuring the headway between two consecutive vehicles on the through-going signal group, using a *Data Collection Point* 1 metre before the conflict zone. Although *Detectors* are also able to measure occupancy in VISSIM, and thus (i) to detect left-turning vehicles, and (ii) determine the headway, *Detectors* in VISSIM collect data only once per second, while *Data Collection Points* have an accuracy 0.01 seconds, regardless of the simulation step size of VISSIM (which is 0.10 seconds by default). That way, *Data Collection Points* are much more accurate to use as a data collection method regarding accepted, and rejected gaps.

Using this data collection method, an accepted gap is defined as a headway (gap) in the through-going signal group (a) that is sufficient for the left-turning vehicle on signal group (b) to safely cross the conflict zone. The accepted gap is found by identifying the headway on signal group (a), and that the *Data Collection Point* on signal group (b) becomes inactive (a vehicle leaves the *Data Collection Point*) during the time interval, given as the headway. Every headway for which it holds that the *Data Collection Point* on signal group (b) does not become inactive, is considered as a rejected gap.

Given the limited time available, only the permitted conflicts of left-turning traffic from North Franklin Street east with opposing through-going and right-turning traffic from North Franklin Street west are considered. Therefore, there is only data collected for this permitted conflict. This means, that given the lane configuration, data is collected for three conflict zones or points, see Figure 5-3: left-turning lane versus consecutively left-through-lane (P1), right-through-lane (P2), and right-turning lane (P3).

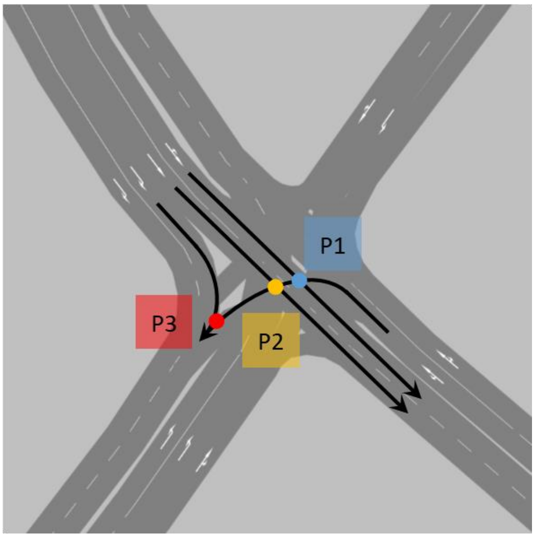


Figure 5-3 | Conflict points for which data is collected.

5.3.5. Results and analysis

Given the limited time for this research, the critical gap is derived using the relatively simplistic Raff's method. The alternative – logistic regression – is considered to be too time-consuming. Moreover, the logistic regression method assumes multiple factors that affect the critical gap size, based on available data. In the VISSIM model, those factors are hard to include. Therefore, Raff's method is used to determine the critical gap size.

Raff's method makes use of the (inverse) cumulative functions for the accepted, and rejected gaps. These cumulative functions are found by grouping the accepted gaps, and respectively the rejected gaps into discrete intervals with a length of 0.5 seconds. That is, every measurement contributes exactly $(1/n)^{\text{th}}$ to the total sample, whereas n is the total number of measurements, as given in Table 5-4. The cumulative functions are plotted with the gap size on the x-axis, and the corresponding fraction on the y-axis. Then it holds that the cumulative function of the accepted gaps is given by $F(A)$, and the cumulative function of the rejected gaps by $F(R)$. To find the critical gap size, the inverse of $F(R)$ is needed, given as $1 - F(R)$. The point where $F(A)$, and $1 - F(R)$ intersect, denotes the critical gap size. This is done per conflict point, per alternative.

Table 5-4 | Number of measurements, per conflict point, for alternatives 0 (default gap time settings), 1 (decreased gap time settings), and 2 (increased gap time settings).

Conflict point		Alternative 0	Alternative 1	Alternative 2
P1	**Total gaps**	1794	1667	1595
	Accepted gaps	1273 (71%)	1201 (72%)	1070 (67%)
	Rejected gaps	521 (29%)	466 (28%)	525 (33%)
P2	**Total gaps**	1287	1163	1289
	Accepted gaps	706 (55%)	642 (55%)	699 (54%)
	Rejected gaps	581 (45%)	521 (45%)	590 (46%)
P3	**Total gaps**	2752	2479	2749
	Accepted gaps	950 (35%)	861 (35%)	940 (34%)
	Rejected gaps	1802 (65%)	1618 (65%)	1809 (66%)

The critical gap size found in VISSIM (section 5.3.5.1, and Table 5-5) is compared to the results found in literature, and guidelines (section 5.3.5.2, and Table 5-1). The deviation of the critical gap size in VISSIM with respect to the critical gap size in literature, and guidelines, is then a measure for how well VISSIM is able to model permitted conflicts.

5.3.5.1. Critical gap size in VISSIM

As stated, the critical gap size in VISSIM is found using Raff's method. The (inverse) cumulative functions are shown in Figure 5-4 on the next page; the results are given in Table 5-5. The results are found by determining for which gap size the (inverse) cumulative functions intersect, per conflict point, per alternative.

Table 5-5 | Critical gap sizes found in VISSIM, per conflict point, for alternatives 0 (default gap time settings), 1 (decreased gap time settings), and 2 (increased gap time settings).

Conflict point	Alternative 0 [s]	Alternative 1 [s]	Alternative 2 [s]
P1	7.6	7.2	7.8
P2	5.4	5.2	5.4
P3	4.6	4.6	4.7

5.3.5.2. Critical gap size in literature

In section 5.2, the critical gap sizes for left-turning traffic in a permitted conflict are already found in literature. These results, as well as the critical gap sizes given in guidelines, are shown in Table 5-1.

Given these results, it is concluded that VISSIM performs good regarding how it models permitted conflicts in relation to gap acceptance when the critical gap size in VISSIM is found to be in the range of 5.5 seconds to 9.0 seconds, as given in Table 5-1. The lower bound is then related to the critical gap size in the AASHTO (2001) guidelines, and the upper bound is based on the results of Zohdy, Sadek, & Rakha (2010) for this particular intersection.

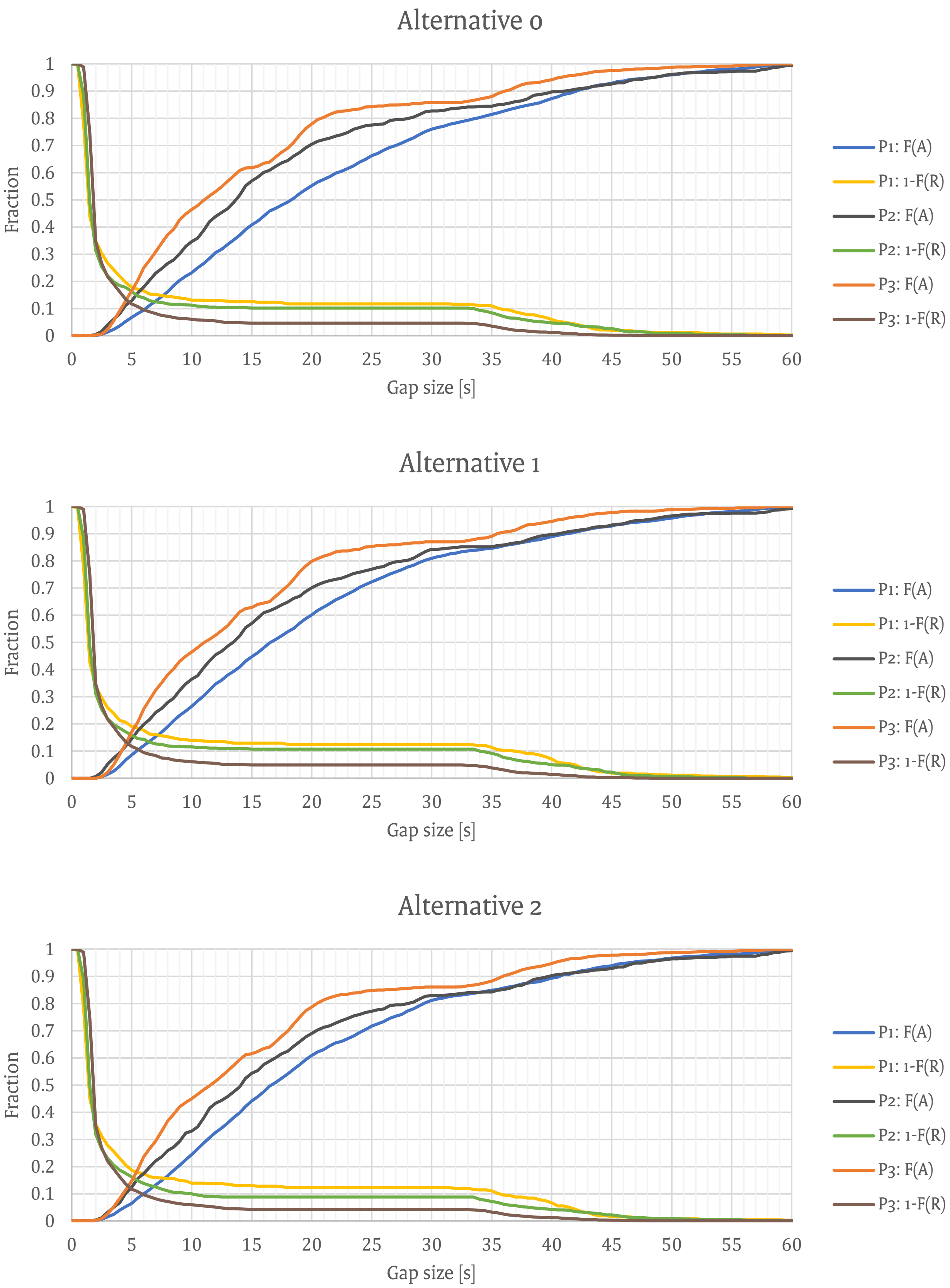


Figure 5-4 | (Inverse) cumulative functions of the accepted ($F(A)$), and rejected gaps ($1 - F(R)$) per conflict point, per alternative.

5.3.6. Conclusion

The results show that the critical gap size differs per conflict point, and per alternative. Regarding the latter, it is found that the settings for the front, and rear gap tend to affect the outcomes only marginally, since the results for alternatives 1, and 2 differ at most 0.4 seconds from the base case alternative with the default settings. Secondly, the results show that the first conflict point (P1) has the largest critical gap, and the third conflict point the smallest (P3). This is not according to the results of Zohdy, Sadek, & Rakha (2010), who found that the second conflict point (P2) has the largest critical gap size (they did not consider P3). This might have to do with sight-obstruction, and size of the conflict zone in which the conflict point lays: in real-life, the gap for second conflict point, or zone, on the right through-going lane, is more difficult to assess, from a driver's point of view, due to potential sight-obstruction from the left through-going lane. This causes the critical gap size to increase, as found by different studies as well. However, in VISSIM this sight-obstruction is not accounted for. In other words, the driver of a left-turning vehicle in VISSIM is able to see through opposing vehicles. Furthermore, the critical gap size of the second conflict zone is smaller due to a smaller conflict zone, because the two signal groups cross each other at a higher angle. The result is a smaller critical gap size for the second conflict point. In the same way, the critical gap size of the third conflict point is also smaller, due to a smaller conflict zone (merging), and no sight-obstruction. It is assumed that VISSIM treats each conflict point the same, while in reality, this might not be the case, given the results from literature when compared to the results from the simulation study, in particular for the second, and third conflict point. Because of the limited time available for this research, this is not investigated further. Therefore, it is recommended to conduct further future research on the way VISSIM simulates gap acceptance for crossing conflicts (e.g. P1) with respect to merging conflicts (e.g. P3).

Nevertheless, the critical gap size as found in VISSIM, in particular for the first, and second conflict point lay within, or close to the predefined range from 5.5 seconds to 9.0 seconds, based on the AASHTO (2001) guidelines, and the results of Zohdy, Sadek, & Rakha (2010). Indeed, the smallest critical gap size is 5.2 seconds, for alternative 1 (decreased gap settings); in the default settings, and the increased gap settings (alternatives 0, and 2), the minimum critical gap size is 5.4 seconds. These values are close to the critical gap size given by the AASHTO (2001) guidelines. The maximum critical gap size is found to range between 7.2 seconds, and 7.8 seconds, which is in the range of 5.5 seconds to 9.0 seconds. The third conflict point, however, shows different results, because the critical gap size here is 4.6 seconds to 4.7 seconds. This 0.8 seconds to 0.9 seconds shorter than the critical gap size of 5.5 seconds given by the AASHTO (2001) guideline, which is used as lower bound. However, the found critical gap size for this conflict is larger than some of the values found in literature, for instance the 4.5 seconds critical gap size as stated by TRB (2000).

Therefore, even though the results of the third conflict point differs from the other two conflict points, the conclusion is that VISSIM models these permitted conflicts sufficiently. Although both the default settings, and the increased gap settings give sufficient results, the conclusion is that the increased gap settings yield the best results, in particular regarding the third conflict zone. That way, the found critical gap sizes in VISSIM lay closest to and/or in the predefined range of 5.5 seconds to 9.0 seconds.

Lastly, the overall conclusion is that the VISSIM simulation model is validated regarding its performance on gap acceptance models, and critical gap size, in relation to permitted conflicts, when using the increased gap settings. Thus, the VISSIM simulation model can be used to perform the model study for this research, and its corresponding objective.

5.4. Main findings

Based on the simulation model validation, the main findings are as follows:

- The literature on analytical gap acceptance models show that most research is done on specific aspects related to permitted conflicts at signalised intersections. That is, because the critical gap size depends on various factors, these factors in particular are investigated. The most often mentioned factors are (i) sight obstruction, (ii) front-of-queue delay, and (iii) permissive phasing with active modes involved.
- Although it was hypothesised that permitted conflicts improve the (intersection) throughput and capacity (see section 4.4), the literature on gap acceptance models state otherwise, as discussed in section 5.2. This relates to the saturation flows, for which it is concluded that it is affected by various aspects, including the critical gap size.
- The VISSIM simulation model is validated on analytical gap acceptance models, with respect to the findings in literature from section 5.2. This is done by simulation an intersection for which data is available from literature, whereas a total of three conflict points are considered. The simulation study results show that the critical gap size differs per conflict point. However, the found critical gap sizes are similar to those found in literature. That is, they lay in the same range, for crossing conflicts. For merging conflicts, different values were found. It is recommended for future work to investigate what the causes of the deviation of the critical gap size of crossing conflicts when compared to merging conflicts are. Nonetheless, the conclusion is that the simulation model is valid in terms of the used analytical gap acceptance model, in relation to permitted conflicts.

6. Permitted conflicts versus protected conflicts: a simulation study

The test of the traffic flow efficiency effects of permitted conflicts with respect to protected conflicts is discussed in this chapter. That is, a simulation study is carried out in which data is collected on the three assessment aspects *Throughput and capacity*, *Queues*, and *Travel times and delays* to see whether or not the implementation of permitted conflicts result in a better performance with respect to protected conflicts. Furthermore, this chapter discusses the hypotheses as formulated in section 4.4 as well, though now with respect to the findings of the simulation study. Therefore, this chapter discusses in fact two steps of the research, as discussed in section X.

The simulation study is done using VISSIM. In the previous chapter, it was concluded that the simulation model is considered as validated to simulate permitted conflicts.

This chapter discusses the simulation study. First, the objective of the simulation study is given, followed by the simulation study set-up. Thirdly, the results are presented, which are then compared with the expectations, and hypotheses as formulated earlier. The chapter concludes with some general remarks.

Additionally, for reference purposes, the variables, introduced in this section, are defined in *Notation and definitions* on pages ix, and x of this thesis as well.

6.1. Simulation study objective

The objective of this simulation study is to determine the traffic flow efficiency effects of permitted conflicts with respect to protected conflicts. That is, it is investigated how the implementation of permitted conflicts might lead to a different performance of the traffic signal controller in terms of throughput and efficiency, queues, and travel times and delays, with respect to the performance of a traffic signal controller with only protected conflicts. This done by simulating a signalised intersection with permitted conflicts, and simulating the same intersection with only protected conflicts, and then comparing the results.

The simulation study aims at identifying how a different conflict type results in a better, or poorer performance of the traffic signal controller in terms of traffic flow efficiency. That way, understanding is developed on what the effects are of permitted conflicts in terms of throughput and efficiency, queues, and travel times and delays. This corresponds to the objective of this research as a whole. Therefore, the results of this simulation study are used to answer the main research question.

6.2. Simulation study set-up

The simulation study set-up relates to the different settings, inputs, and alternatives used. First, the network lay-out is discussed, followed by the simulation period, number of runs, alternatives, implemented traffic safety measures, and model inputs. Lastly, the data collection is discussed.

6.2.1. Network lay-out

The simulation study uses a synthetic signalised intersection, to exclude the different details in geometric intersection design of real-life signalised intersections, such as the radii of corners. Moreover, a symmetric, four-approach synthetic signalised intersection is used. That way, the geometric design of each intersection approach is identical. As a consequence, the properties of the conflict points for one approach are identical to those of the other three approaches as well. That way, the number of identical conflict points is maximised, thereby reducing the time needed to perform the simulation study. Therefore, the choice to use a symmetric synthetic signalised intersection is a rather pragmatic one. However, such a synthetic intersection has to be designed as well, according the guidelines, and considering the traffic signal control design elements, and traffic safety conditions as mentioned in sections 4.1 and 4.2. These conditions, as well as other design elements, are applied on the design of a synthetic signalised intersection, with permitted conflicts, in this section.

The Dutch guidelines on signalised intersections given by CROW (2006) do not specify, nor quantify the geometric intersection design elements given as traffic safety conditions. However, in the guidelines for geometric road design, some of these conditions are specified, and/or quantified. Indeed, CROW (2012) states the following (CROW, 2006; CROW, 2012):

i. A permitted conflict in general may not be applied for crossing signal groups, or movements, literally formulated as signal groups, or movements that cross perpendicular (see Figure 2-1);
ii. Permitted conflict type 2 is not allowed in the case of a bidirectional bicycle path or lane.
iii. When permitted conflict type 2 is combined with permitted conflict type 1, the left-turning signal group may not have more than one lane;
iv. When permitted conflict type 2 is combined with permitted conflict type 1, there may not be a bicycle path, but rather a bicycle lane;
v. The intersection itself must be small scale (no more than two lanes on the crossing roads);
vi. There has to be enough space on the intersection for vehicles to wait for their turn;
vii. The intersection design might not lead to blocking of the view while vehicles are waiting;
viii. The median might not be not too wide.

Nevertheless, several conditions are still not quantified in the Dutch guidelines. For instance condition (viii) on the median width is still not specified. Therefore, American guidelines are used as well. In the gap acceptance studies including permitted conflicts at signalised intersections, it was found that the median width influences the critical gap size, and thus that the median should not be too wide. These studies referred to the American guidelines. For instance, AASHTO (2001) stated that when a median is wider than 1.8 metres to 2.4 metres, sight distance problems occur due to sight-obstruction – assuming a left-lane width of respectively 3.6 metres to 3.0 metres. These recommended median widths are less than stated by Harwood, Pietrucha, Wooldridge, Brydia, & Fitzpatrick (1995), who found that a median width of less than 4.0 metres to 4.6 metres is sufficient at (sub)urban signalised intersections. Although they also propose measures to mitigate sight-obstruction issues (e.g. offset of left-turning lanes within the median), they also state that these measures are to be applied on rural signalised intersection, in general. Therefore, the guidelines provided by AASHTO (2001) are used. Then, to minimise potential sight-obstruction problems, the median width is to be designed at 1.8 metres. That way, both conditions (vii) and (viii) are addressed.

Taking these conditions into account, the synthetic signalised intersection is designed as shown in Figure 6-1 on the next page. The synthetic intersection includes four approaches that cross each other perpendicularly, thus at a 90° angle. Each approach has two lanes. The right lane is for both through-going traffic, and right-turning traffic, the left lane is for left-turning traffic only. The vehicle generation of each approach originates from one lane, which later splits into two lanes. That way, blocking is modelled is as well, whereas blocking is defined as a queue length exceeding the length of the two-lane section of each approach. Furthermore, bicycle paths, and sidewalks are included on each approach. The bicycle paths are one-directional. Since bicycle paths are considered, the aforementioned condition (iv) on bicycle lanes instead of bicycle paths is not met in alternative (3), as will be explained in section 6.2.4, because in this alternative, left-turning traffic has a permitted conflict with through going bicyclists as well, whereas condition (iv) states that this is only allowed in the case of a bicycle lane. However, the fact that condition (iv) is not met in alternative (3) is considered as acceptable, because if bicycle lanes would be used, more, and other conditions would not be met, for instance conditions (vi), and (vii), regarding respectively the size of the waiting area, and risk of sight-blockage. Moreover, in practice it is found that condition (iv) is not met as well, see for instance the intersection depicted in Figure 3-1f. In Figure 6-2 on the next page, a cross section of an approach 10 metres before the stop line is given. The dimensions given in this cross section are applied on all four approaches for they are identical. The waiting area for right-turning vehicles who have to yield for bicyclists, and pedestrians is observed to be sufficient to prevent continuous blocking for through-going traffic from the same lane. That is, in VISSIM, through-going vehicles can pass the intersection without much hindrance due to waiting vehicles that want to turn right.

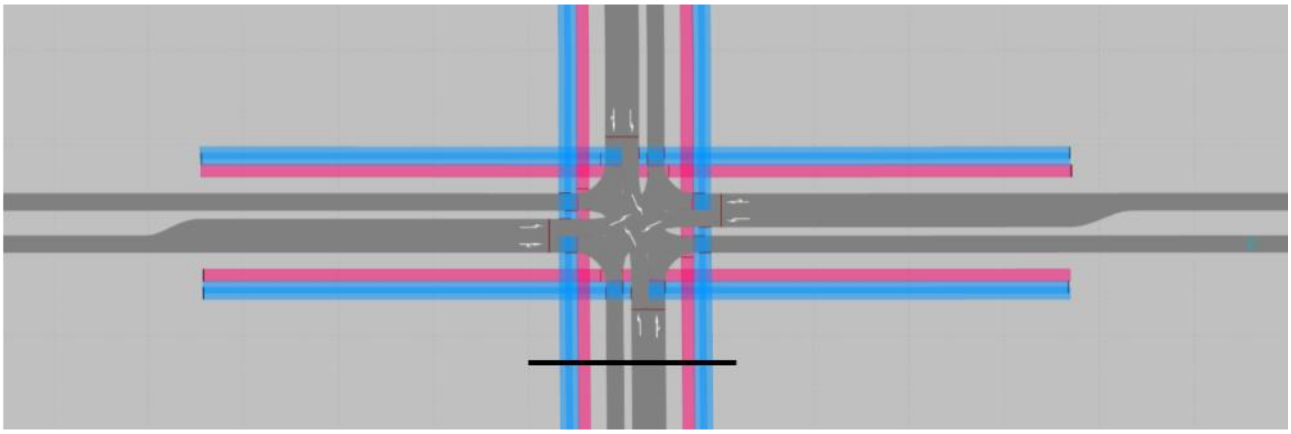


Figure 6-1 | Synthetic signalised intersection in VISSIM, with bicycle paths in pink, and sidewalks in blue, and the location of the cross section (Figure 6-2) at the black line.

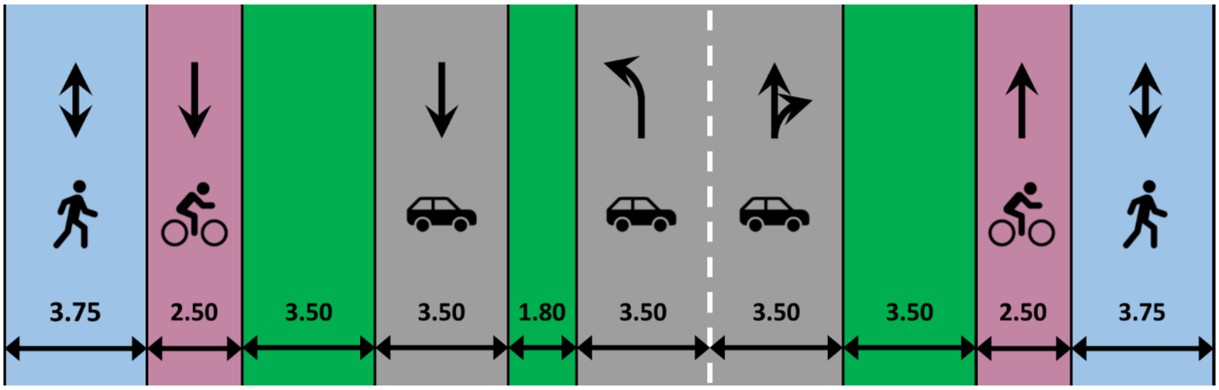


Figure 6-2 | Cross section of an approach on the synthetic signalised intersection (dimensions in metres).

6.2.2. Simulation period

Each run of the simulation consists of 4200 simulation seconds (70 simulation minutes). In the data collection, and data analysis, only the middle hour is used, thus the first, and last 300 simulation seconds (5 simulation minutes, cumulative 10 simulation minutes) are not included. This means that data is collected, and analysed for a simulation period of 3600 seconds (60 simulation minutes). That way, the data is analysed in the period when the signalised intersection is fully functional. Indeed, during the first 300 simulation seconds, the network is assumed to be filling itself, which might cause disturbances in the data. The emptying of the network might also cause disturbance, hence the removal of the last 300 simulation seconds from the analysis. Moreover, this way, the data is already scaled to values per hour.

6.2.3. Number of runs

The number of runs determines the reliability of the evaluation results. The number of runs is computed using a limited number of pilot runs, and is based on the standard deviation of the data collected in these pilot runs. This results in the following equation given by WSDOT (2014):

$$N \geq z^2_{\frac{\alpha}{2},n-1}\left(1+\frac{\xi^2}{2}\right)\left(\frac{\sigma_s}{\sigma_a}\right)^2 \tag{6-1}$$

In this equation, α represents the reliability [%], N the number of simulation runs [#], σ_s, and σ_a represent respectively the standard deviation of the pilot sample, and the accepted standard deviation [-], ξ equals the normal distribution excess value [-], and $z_{\alpha/2,n-1}$ is the value of student-t distribution for a given reliability α [-], and pilot sample size n [#]. For the normal distribution excess value ξ, it holds that $\xi = 0$ when the average values are used to compute the pilot sample standard deviation, therefore yielding:

$$N \geq z^2_{\frac{\alpha}{2},n-1}\left(\frac{\sigma_s}{\sigma_a}\right)^2 \tag{6-2}$$

This equation could be reduced further, if the accepted standard deviation σ_a would be set equal to the sample standard deviation σ_s, thus $\sigma_a = \sigma_s$, yielding:

$$N \geq z^2_{\frac{\alpha}{2},n-1} \tag{6-3}$$

Now, the number of simulation runs can be computed, given a value for $z_{\alpha/2,n-1}$, and thus a given value for reliability α, and pilot sample size n. However, given the limited time for this research, this process is reversed. Instead, a number of runs N is selected, after which the corresponding value for $z_{\alpha/2,n-1}$, and thus reliability α, is computed, given a pilot sample size n.

For the pilot study, a pilot sample size n of 6 is used, thus $n = 6$, and the number of runs N^* [#] is set on 10, thus $N = 10$. Then, it is found that $z_{\alpha/2,6-1}$ equals approximately 3.162, which means that a reliability of approximately 97.5% is achieved.

On the other hand, if the sample standard deviation σ_s, and accepted standard deviation σ_a are used, it is found that, based on the pilot results for delay d [s/pce], the sample standard deviation equals $\sigma_s = 18.418$ s/pce, with an average delay of 46.217 s/pce. Using an accepted standard deviation of $\sigma_a = 15.000$ s/pce, with the same pilot sample size $n = 6$, and number of runs $N = 10$, it was found that $z_{\alpha/2,6-1}$ equals approximately 2.575. Now, this means that a reliability of the evaluation results is achieved of approximately 95%.

Although both computations showed an approximate reliability of 95% to 97.5% of the evaluation results, which is rather high, and are therefore to be considered as fairly certain evaluation results, it must be stated that in fact the evaluation is quite limited. Indeed, only one intersection type, which is not a real-life intersection, is considered. In the same way, only a limited number of alternatives, and traffic flow volume sets are considered. Altogether this implies that even though the hereafter presented evaluation results are statistically reliable, more certain, and reliable results ought to be found by performing this evaluation for more (real-life) intersection, including more alternatives, and scenarios. This is recommended as future work.

6.2.4. Alternatives

The alternatives that are simulated include only part of the various types of permitted conflicts. As stated in the previous chapter, the scope is narrowed down to only include permitted conflict types 1 and 2 explicitly. The other permitted conflict types are excluded for two reasons: (i) the current practice in the Netherlands does not include those permitted conflict types, or the implementation of that type is prohibited, and (ii) there is a limited amount of time available for this research, meaning that it would take too much time to include all permitted conflict types. Lastly, it must be noted that in strict terminology, permitted conflict types 3 and 4, in fact, are implemented in the Netherlands, though with a very short protected phasing time, namely respectively as a pre-start for active modes in the case of a permitted conflict type 2, and when in a vehicle-actuated traffic signal controller one of the two permitted conflict signal groups terminates its green phase before the other is terminated. However, since the minimal time setting for a pre-start is set on $t_{ps,min} \geq 0$ s, it is assumed that permitted conflict type 3 is neither formally, nor explicitly implemented in the Netherlands, in particular when considering permitted conflict type 1, and is therefore excluded from this research. Nonetheless, permitted conflict type 4 is only implicitly included in relation to vehicle-actuated traffic signal controllers.

Given the scope of the research in relation to the included permitted conflict types, the simulation study includes a total of four alternatives. The following alternatives are simulated:

0. Base case: conflict-free intersection (no permitted conflicts, only protected conflicts);
1. Permitted conflicts between car signal groups (type 1);
2. Permitted conflicts between a car signal group versus an active mode signal group (type 2);
3. Combination of alternatives (1) and (2).

The base case alternative describes the current practice in the Netherlands, as explained earlier in section 2.2.1, where protected conflicts are more commonly implemented. This is the reference alternative, meaning that the other three alternatives are compared to the base case. Then, the other three alternatives describe the situation in which permitted conflicts are implemented.

6.2.5. Traffic safety measures

As discussed before, several traffic safety related measures are to be taken on a signalised intersection when implementing permitted conflicts, at least in the Netherlands. Some of these measures are already addressed in the geometric design of the synthetic intersection – i.e. median width, lane configuration, etc. Other measures, such as warning signs, are not relevant in this simulation study. Nevertheless, the traffic safety measures are explicitly implemented. In short, this relates to the following traffic safety measures:

- Geometric intersection design: the synthetic intersection is designed as (i) a small scale intersection (no more than two lanes per approach), (ii) with median widths of 1.8 metres, according to American guidelines, implying that road users are able to see each other, (iii) sufficient space on the intersection for vehicles to wait for their turn, (iv) no blocking of the view while vehicles are waiting, and (v) no bidirectional bicycle paths;
- Synchronised start: for permitted conflict type 1, a synchronised start is implemented in the traffic signal control design. This means that conflicting car signal groups with permissive phasing, start their green phase at the exact same moment, e.g. the green phase of a left-turning movement in a permitted conflict with the opposing through-going movement, start at the same moment as the green phase of the opposing through-going movement;
- Pre-start: for permitted conflict type 2, a pre-start is implemented in the traffic signal control design. In other words, the green phase of an active mode signal group start before the green phase of a permitted conflicting

car signal group. For this, the pre-start time $t_{ps} = 1$ s is used. Thus, e.g. the green phase of signal group 28 starts 1 second before the green phase of permitted conflicting signal group 02;

- Speed: the synthetic intersection is designed as a small scale intersection, with the principle of being an urban intersection, thus with a speed limit of 50 km/h. In the curves, *reduced speed areas* are used to lower the speed further, to 20 km/h to 30 km/h.
- Traffic flow volume: the traffic flow volumes are listed in Table 6-1 in section 6.2.6.2. Assuming a saturation flow per lane of 1200 pce/h (the average saturation flow as measured for the alternative with both permitted conflicts, see section 6.3.1, and appendix B), this means that the load ratio varies between 0.08 and 0.42, implying an assumed low probability of overflow of a permitted conflict signal group, since at most, not half of the capacity is used. However, it must be noted that overflow also relates to the degree of saturation, which means that the ratio between the green time, and cycle time also plays a role, as explained in section 4.3.1.

6.2.6. Model inputs

The model inputs relate to (i) the settings for the speeds, acceleration, and deceleration, (ii) the traffic flow volumes, and (iii) traffic signal controller settings.

6.2.6.1. Speeds, acceleration, and deceleration settings

The speeds are set according to the maximum speeds that are in force on the four approaches, namely 50 km/h, based on the traffic safety measures. Thereto, a new speed distribution is constructed representing the maximum speed. The speed distribution accept some deviation of the maximum speed, namely 2.5 km/h. The used speed distribution is 50 ± 2.5 km/h. At the curves, the speeds are lower, as introduced above: right-turning curves have a speed setting of 20 km/h, and left-turning curves 30 km/h. The different speeds for right-turning, and left-turning are based on the geometric intersection design: right-turning movements have a smaller curve radius. Regarding the settings for the acceleration, and deceleration, the default settings in VISSIM are used.

6.2.6.2. Traffic flow volumes

Because the considered signalised intersection is a synthetic intersection, no data on traffic flow volumes is known. Therefore, traffic flow volumes are generated, and assumed, whereas the assumptions are loosely based on the default inputs used in COCON. This is done per signal group (see Figure 6-3 on the next page for signal group numbers[*]). Also, only passenger cars are used in the simulation, thus the traffic flow volume in [pce/h] equals the traffic flow volume in [veh/h]. Furthermore, three scenarios with different traffic flow volume sets are considered, each with a different assumption on what the main road is. In fact, more scenarios could be applied, however, since the intersection is symmetric, all possible scenarios can be brought back to three. Scenario (1) assumes that all directions have identical traffic flow volumes, and thus that all approaches have the same traffic flow volume . Scenario (2) assumes that the north-south corridor is the main road with the highest traffic flow volumes, and scenario (3) assumes that the south-east movement and visa versa has the highest traffic flow volumes, see Table 6-1.

It must be noted that it is possible that, given the random arrival pattern in VISSIM (the default setting), a signal group might not have a green phase during a cycle. That is, if no green phase request for a signal group is made,

[*] It must be noted that the Dutch guidelines forbid the use of a separate signal group for a left-turning movement when a permitted conflict is applied. That is, a separate left-turning signal group is controlled with an arrow symbol as display, which may only be applied on protected conflicts (CROW, 2006). Therefore, in the traffic signal controller, the left-turning signal group is not present. Instead, both lanes (left-turning, and through-going and right-turning combined), have the same signal group, and display when permitted conflicts are implemented.

that signal group will not receive a green phase. Therefore, it is possible that during a cycle, certain permitted conflicts are not realised. In other words, that during a cycle, for e.g. a left-turning movement and its opposing through-going movement, which have a permitted conflict, the green phase for only the through-going movement is realised, because the left-turning movement did not have a request, implying that the conflict is then controlled as a protected conflict.

Given the fact that four alternatives are simulated, using three scenarios regarding traffic flow volumes, this means that in total 12 situations are simulated, and thus analysed.

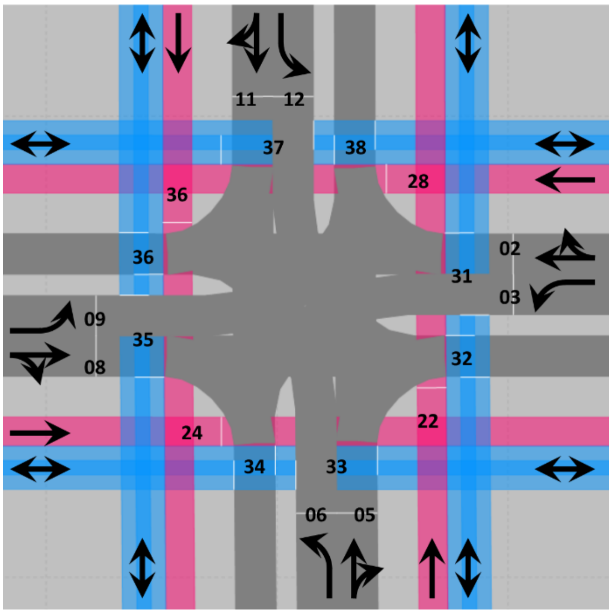


Figure 6-3 | Signal group numbers of the synthetic signalised intersection.

Table 6-1 | Traffic flow volumes per signal group per scenario.

Signal group	Scenario 1 *q* [pce/h] or [#/h]	Scenario 2 *q* [pce/h] or [#/h]	Scenario 3 *q* [pce/h] or [#/h]
02	400 (200 through; 200 right)	500 (400 through; 100 right)	500 (100 through; 400 right)
03	200	100	100
05	400 (200 through; 200 right)	200 (100 through; 100 right)	200 (100 through; 100 right)
06	200	100	100
08	400 (200 through; 200 right)	500 (400 through; 100 right)	200 (100 through; 100 right)
09	200	100	100
11	400 (200 through; 200 right)	200 (100 through; 100 right)	200 (100 through; 100 right)
12	200	100	400
22	200	200	200
24	200	200	200
26	200	200	200
28	200	200	200
31/32	200	200	200
33/34	200	200	200
35/36	200	200	200
37/38	200	200	200

6.2.6.3. Traffic signal controller settings

6.2.6.3.1. Clearance times

The clearance times are computed for all conflicts, see appendix C. That way, the resulting clearance time matrix represents the matrix for a conflict-free traffic signal controller, thus protected conflicts only. The clearance times are computed using the formulas provided by the Dutch guidelines (CROW, 2013):

$$t_{\text{exit}} = \frac{L_{\text{exit}} + l_{\text{exit}}}{v_{\text{exit}}} \tag{6-4}$$

$$t_{\text{enter}} = t_r + \sqrt{\frac{2L_{\text{enter}}}{a_{\text{acc}} + a_{\text{dec}}}} \tag{6-5}$$

$$t_{\text{clear},i,j} = t_{\text{exit},i} - t_{\text{enter},j} \mid t_{\text{clear},i,j} \geq 0 \tag{6-6}$$

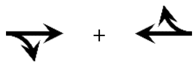
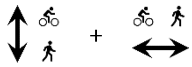
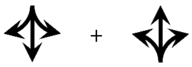
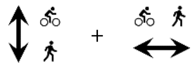
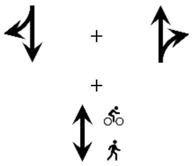
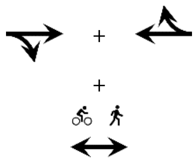
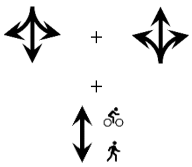
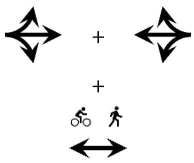
In these formulas, the clearance time t_{clear} [s] is computed as the difference in the time t_{exit} [s] needed for signal group i to clear the conflict zone, and the time t_{enter} [s] needed for conflicting signal group j to reach the conflict zone. The Dutch guidelines explicitly state that the clearance time might not be negative, hence the condition $t_{\text{clear}} \geq 0$ s (although this condition is about to be removed from the Dutch guidelines, the condition is still used in this research, for simplicity). Furthermore, t_{exit} [s], and t_{enter} [s] are separately computed, whereas the former depends on the distance L_{exit} [m] from the stop line to where the conflict zone is completely cleared, the vehicle length l_{exit} [m] of vehicle exiting conflict zone, and the speed v_{exit} [m/s] of a vehicle clearing the conflict zone. In general, the values $l_{\text{exit}} = 6$ m for passenger cars, and $v_{\text{exit}} = 12$ m/s are applied. The entrance time t_{enter} includes the distance L_{enter} [m] from the stop line to the conflict zone, and the acceleration rate a_{acc} [m/s²], and deceleration rate a_{dec} [m/s²] of vehicles at the stop line. Also, the reaction time t_r [s] is included explicitly. Then, fixed values are used for the latter three variables, namely $a_{\text{acc}} = a_{\text{dec}} = 2.5$ m/s², and $t_r = 1$ s.

The clearance times are computed using a specialist computer program OTTO in which the paths of signal groups on an intersection are drawn, after which the program computes the clearance times automatically, using the formulas listed above. The resulting clearance time matrix for all conflicts is given in appendix C, where the underlined clearance timers correspond to conflicts that might be controlled as permitted conflicts, and should therefore be removed from the matrix if permissive phasing is applied.

6.2.6.3.2. Traffic signal control design

The simulated traffic signal controller is a vehicle-actuated traffic signal controller. The design of this vehicle-actuated traffic signal controller is based on the settings for a fixed time traffic signal controller. Given the alternatives, and traffic flow volume scenarios as explained in section 6.2.6.2, a total of twelve fixed time traffic signal controllers are designed. That is, for each scenario per alternative, a fixed time traffic signal controller is designed using COCON to determine the computed cycle time, and optimal block sequence. It must be noted that the block sequences per scenario were found to be identical, and thus only differ per alternative as listed in section 6.2.4, see Table 6-2. Furthermore, it must be noted that the optimal block sequence is defined as the block sequence corresponding to the minimum cycle time, based on the maximum conflict group (thus not on the critical path of the signal groups*), and maximum flexibility. In this context, flexibility relates to how the progression from one block to another, occurs smoothly. In other words, if in block (a) a signal group has no request, and a conflicting signal group in the next block (b) does have a conflict, that the signal group in block (b) can already receive green in block (a). This is then considered as an alternative realisation, or an advanced realisation. If such alternative, or advanced realisations are possible due to a favourable block sequence, the block sequence is considered as a flexible block sequence.

Table 6-2 | Optimal block sequence per alternative.

Alt.	Block I	Block II	Block III	Block IV	Block V
0					
1				N/A	N/A
2					N/A
3			N/A	N/A	N/A

It can already be seen that the number of blocks per alternative differs, depending on the type of permitted conflict(s) implemented. Indeed, if both permitted conflict types (1), and (2) are implemented, only two blocks are considered, versus five in the conflict-free (base case) traffic signal controller.

6.2.7. Data collection and processing

The traffic simulation model software VISSIM includes multiple methods to collect data on various performance indicators. The relevant methods are discussed in this chapter per assessment aspect: (1) throughput and capacity, (2) queues, and (3) travel times and delays. Also, the way the data is processed is discussed, since the raw data might not be suitable as input for the analysis. For all collected data it holds that data is collected for motorised traffic, active modes, and PT.

6.2.7.1. Throughput and capacity

The throughput and capacity assessment aspect includes the performance indicators: intersection throughput, intersection load ratio, and degree of saturation. The data on these parameters is collected in VISSIM. Since the data collection, and analysis period of the simulation is set on 3600 simulation seconds (60 simulation minutes, see section 6.2.2), the data is aggregated per hour. In other words, for instance traffic flow volume data is collected in vehicles per hour (converted to pce per hour).

In Figure 6-4 on the next page an overview is given of the different performance indicators on which data is collected, and how the performance indicators relate to each other. First, the traffic flow volumes, used to

* COCON uses two methods to determine the cycle time, and block sequence: the classical method using only the maximum conflict group, and the modern method (formally known as GRAPHIUM) uses both the maximum conflict group, and the critical path (DTV Consultants, 2017). In this research, the classical method is used. However, for some scenarios, the results of modern method are tested as well, which yielded identical results as the classical method.

determine the intersection throughput, are in fact input for the simulation model. Therefore, the traffic flow volumes are derived from the *O/D-matrices*, and denote the traffic demand. The traffic demand is simulated, and using *data collection points* on the stop lines, data is collected on how much of the traffic has passed the stop line. Then, this is the saturation flow, which is used to determine the load ratio (formula (3.2)), both per signal group, and for the intersection. Lastly, the degree of saturation is derived using the load ratio, and the fraction of effective green time per cycle (formula (3.3)). The latter is processed using *raw signal timing data*, from the traffic signal controller in VISSIM, on the cycle time, and green time. The green time is used to determine the effective green time, which denotes the time that traffic is being served.

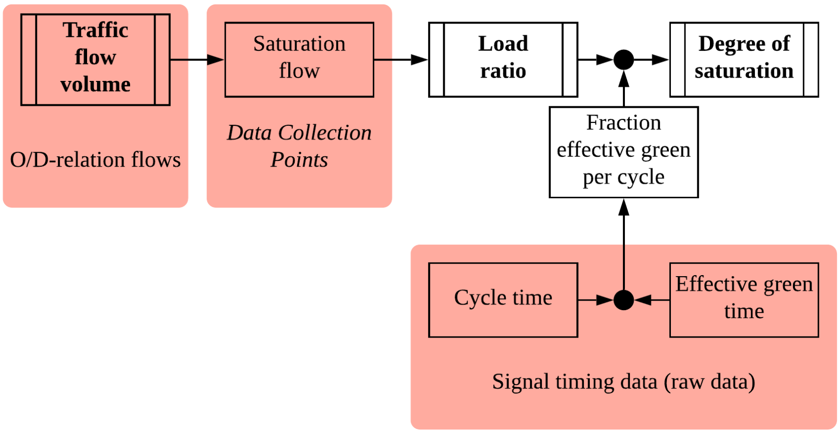


Figure 6-4 | Data collection for throughput and capacity, including the relations between the performance indicators. The red boxes denote output of VISSIM, the white boxes represent calculated results.

6.2.7.2. Queues

The assessment aspect queues relates to (i) queue lengths, and (ii) stops. These performance indicators can directly be measured in VISSIM. Indeed, using *queue counter measurements*, data on (i) queue lengths is collected. *Delay measurements* are used to collect data on (ii) stops. Again, the collected data is aggregated per hour, meaning that for instance the data on stops is given as number of stops per pce per hour.

It must be noted that the *queue counter measurements* in VISSIM make use of conditions. These conditions describe the situation for which it holds that a queue is present. The conditions relate to the speed in the queue, the headway, and maximum queue length, see Table 6-3 on the next page. As long as all these conditions are met, the *queue counter measurement* measures a queue. Thus, e.g., as soon as the speed reduces to less than 5.0 km/h, it is assumed that there is queue, which is not dispersed until the speed increases to more than 10.0 km/h. This means that, according to VISSIM, a queue might suddenly disappear if vehicles start driving faster than 10.0 km/h, while this might still be considered as a queue in practice. This is best illustrated with the following example: if the last vehicle in the queue is relatively far upstream of the stop line, the queue length is high, but becomes zero as soon as the speed of the queue exceeds 10.0 km/h, while there is still a moving queue. Although different values for the aforementioned conditions might yield results that resemble queue lengths as measured in practice better, it is assumed that the default settings of VISSIM suffice. The queue length is then averaged per analysis period. This implies that the average queue length also includes the parts of the analysis period during which no queue was present.

Table 6-3 | *Queue counter measurement* conditions for which it holds that a queue is present.

Condition	Definition
Minimum speed in queue $v^Q_{\min}$ [km/h]	$v^Q_{\min} < 5.0$
Maximum speed in queue $v^Q_{\max}$ [km/h]	$v^Q_{\max} > 10.0$
Maximum headway in queue H^Q [m]	$H^Q = 20.0$
Maximum queue length $L_{\max}$ [m]	$L_{\max} = 500.0$

The location of the data measurement methods (*queue counters*, and *delay measurements*) affect the outcomes of the analysis. In Table 6-4, the location of the relevant data measurement methods are given per performance indicator, per type of conflict (protected conflict, versus permitted conflict). It must be noted that for the *delay measurements* to collect data on the stops, and delays, a section of the network is covered instead of a fixed point, due to the settings for these measurements in VISSIM.

Table 6-4 | Data measurement method locations for *queue counters*, and *delay measurements*.

Performance indicator	Data measurement method	Location for protected conflicts	Location for permitted conflicts
Queue lengths	*Queue counter measurements*	Stop line	Stop line, and edge of conflict zone
Stops	*Delay measurements*	Start of network until stop line	Start of network until stop line, and until edge of conflict zone
Delay	*Delay measurements*	Start of network until stop line	Start of network until stop line, and until edge of conflict zone

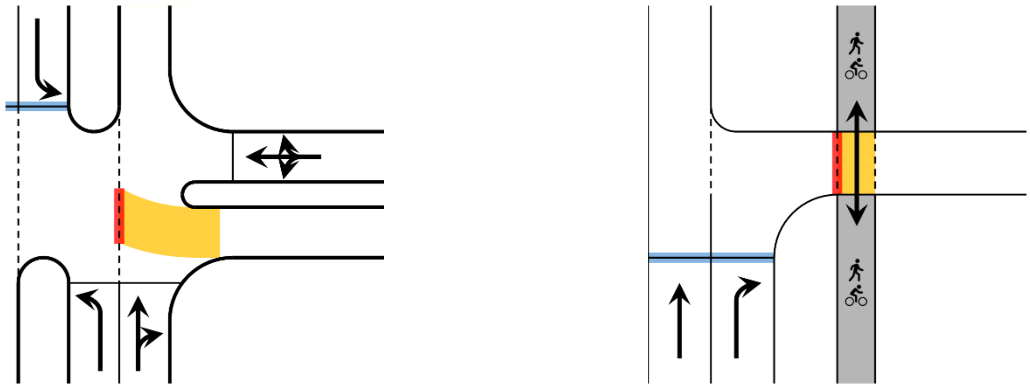


Figure 6-5 | Example of data collection locations for a permitted conflicts types 1 (a), and 2 (b), with data collection at the stop line in blue, conflict zone in yellow, and data collection at the edge of the conflict zone in red.

As can be seen in Table 6-4, the data measurement for permitted conflicts is somewhat different than for protected conflicts. The reason for the different locations for data measurements, is that with protected conflicts, the queue is always upstream of the stop line, at least when excluding red-light-running. However, with permitted conflicts, the queue might be standing downstream of the stop line as well, namely between the conflict zone and the stop line. In reality, there is another cause for a queue standing downstream of the stop line, also for signal groups with protected conflicts: spillback from a downstream intersection. However, this spillback is not considered in this research, since a single, isolated signalised intersection is simulated, see also section 1.2. The same principle holds for where stops, and delays occur, namely in queues. Therefore, it is necessary to place the data measurement points on queue lengths, stops, and delays downstream of the stop line, thereby including the queue between the conflict zone and the stop line. For protected conflicts, this is irrelevant, assuming that during green all vehicles can clear the conflict area. Nevertheless, the data of permitted conflicts is also collected on the stop line, because that way the queue length, number of stops, and delays in the queue upstream of the stop line is investigated. This enables a distinction between the queue lengths, stops, and delays due to the permitted conflict, and the traffic signal controller. In Figure 6-5 on the previous page, this principle is visualised. The blue line represents the stop line, the red line is the edge of the conflict zone, which is yellow. The queue lengths, stops, and delays of through-going motorised traffic in e.g. Figure 6-5b are then measured on the stop line. Right-turning traffic has a permitted conflict with active modes. For this right-turning traffic, the queue lengths, stops, and delays are measured on the red line – the edge of the conflict zone – as well. The same principle holds for car signal groups in a permitted conflict in Figure 6-5a.

6.2.7.3. Travel times and delays

The assessment aspect of travel times and delay include the performance indicators cycle time, and delays. Three of these performance indicators can directly be measured from VISSIM. First, the cycle time can be derived from the *raw signal timing data*, as discussed in section 6.2.7.1 as well. Secondly, data on delays are collected using *delay measurements*. As briefly mentioned in the previous section, *delay measurements* collect data on a section of the network. For delays, the start of the section is set on the start of the network. The end of the data measurement section, is either the stop line, or the edge of the conflict zone. The latter is relevant for signal groups with a permitted conflict, as discussed in section 6.2.7.2.

6.3. Results

The results are presented in three parts. First, the results for throughput and capacity are given in terms of intersection throughput, load ratio, and degree of saturation. Secondly, the results for queues are presented, in terms of queue lengths, and the number of stops. Thirdly, the travel time and delay results are given by presenting the cycle times, and delays.

In all three parts, the results of the permitted conflict types (alternatives 1, 2, and 3) are presented as relative values with respect to protected conflicts (base case alternative 0). That is, the results are given as percentages denoting how much the performance of permitted conflicts deviates from the performance of protected conflicts using a relative value. Therefore, it holds that the performance of protected conflicts is indexed at 100%. In other words, the performance of protected conflicts is considered as reference performance, given as 100%.

It must be noted that the results are given per mode, thus for cars, bicycles, and pedestrians. Also, the results for all modes combined (“total”) are presented. The results per mode are the result of averaging the results per signal group for a certain mode, whereas signal groups 02 to 12 are car signal groups, 22 to 28 bicycle signal groups, and 31 to 38 pedestrian signal groups. The average of all signal groups 02 to 38 yields the “total” result, whereas it must be noted that the data is collected at the stop line. The results of individual signal groups are given in appendix B, unless stated otherwise, thereby including the absolute results.

6.3.1. Throughput and capacity

The results for throughput and capacity show that the saturation flow has indeed decreased, see Figure 6-6 on the next page. In the base case alternative with only protected conflicts, the saturation flow s ranges between approximately 2100 pce/h, and 2500 pce/h, which is rather high, given the saturation flow of 1900 pce/h to 2000 pce/h as found in the Dutch guidelines CROW (2006), for instance, while with permitted conflicts, the saturation flow decreases with 29% to 67%, depending on the signal group, and type(s) of permitted conflicts that are implemented. For instance, when only permitted conflict type 2 is implemented, the reduction of the saturation flow ranges between 29% and 39%, while with both permitted conflict types 1, and 2 implemented, the saturation flow decreased with 29% to 67%, whereas the left-turning signal groups 03, 06, 09, and 12 show the largest reductions.

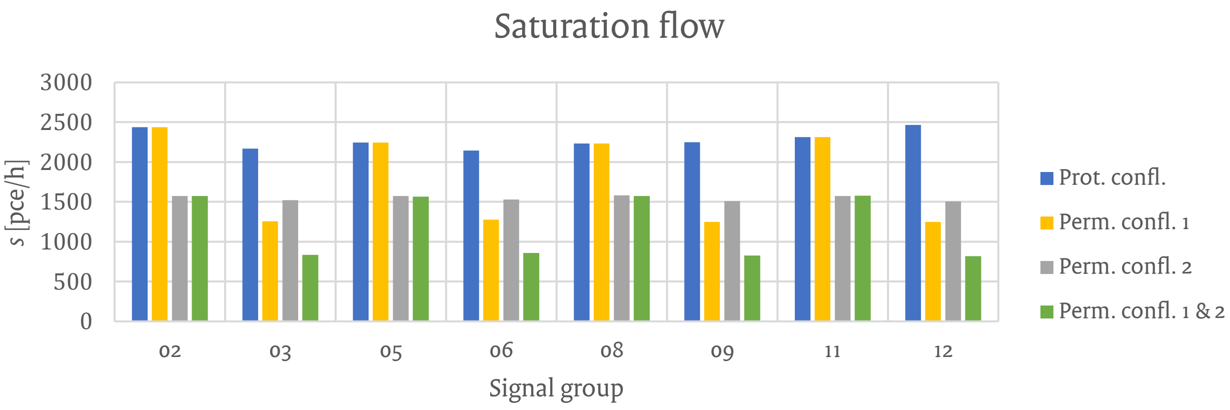


Figure 6-6 | Saturation flow *s* per signal group (car only), with protected conflicts (prot. confl.), and permitted conflicts (perm. confl.).

On the other hand, the implementation of permitted conflicts resulted in improved intersection throughput, though it is rather marginal, see Figure 6-7 on the next page. That is, based on the measured traffic flow volume q, it can be seen that, in general, the intersection throughput improved with approximately 1% at most. Combined with the rather severe reduction of the saturation flow, this results in an increase of the load ratio y, ranging from load ratios that are 18% to 118% higher than in the base case alternative (protected conflicts), see Figure 6-8 on the next page. It can be seen that this depends on the considered permitted conflict type(s) that is/are implemented, and the traffic flow volume scenario. Nonetheless, it must also be noted that although an increase of the load ratio of 118% seems rather severe, in absolute values, it is an increase from 0.07 to 0.16, implying that the load ratio is still relatively low, as can be seen in appendix B as well.

Next, the green time T_G is somewhat increased, see Figure 6-9 on page 51, though this is mainly the result of green times for bicycle signal groups up to three times as high as with protected conflicts. This is due to a change from multiple realisations to one realisation per cycle: with protected conflicts, bicycle signal groups have multiple short green phases per cycle, while with permitted conflicts, this becomes one long green phase due to the traffic safety condition on pre-start, and the coupling with the parallel car signal group as way to prevent permitted conflict types 3 and 4. For signal groups with only cars, the green times changes range around $\pm 25\%$ with respect to protected conflicts.

The degree of saturation x is found to increase as well in most cases, though less severe than the load ration, see Figure 6-10 on page 51. This is due to increased green time, but mostly because of a decreased cycle time, as shown in Figure 6-13 on page 53, which will be discussed in section 6.4.3. Moreover, in one case, the degree of saturation even decreased. Regardless, the increase of the degree of saturation ranges between approximately 6% to 56%, when considering the signal groups at the stop line. This corresponds to absolute values of 0.85 to 1.14, implying (near-)oversaturated conditions. In fact, it is found that in the case of implementation of either permitted conflict type 2, or both types 1 and 2, the degree of saturation increases to values representing (near-)oversaturation, thereby ranging between 0.89 to 1.14, see also appendix B.

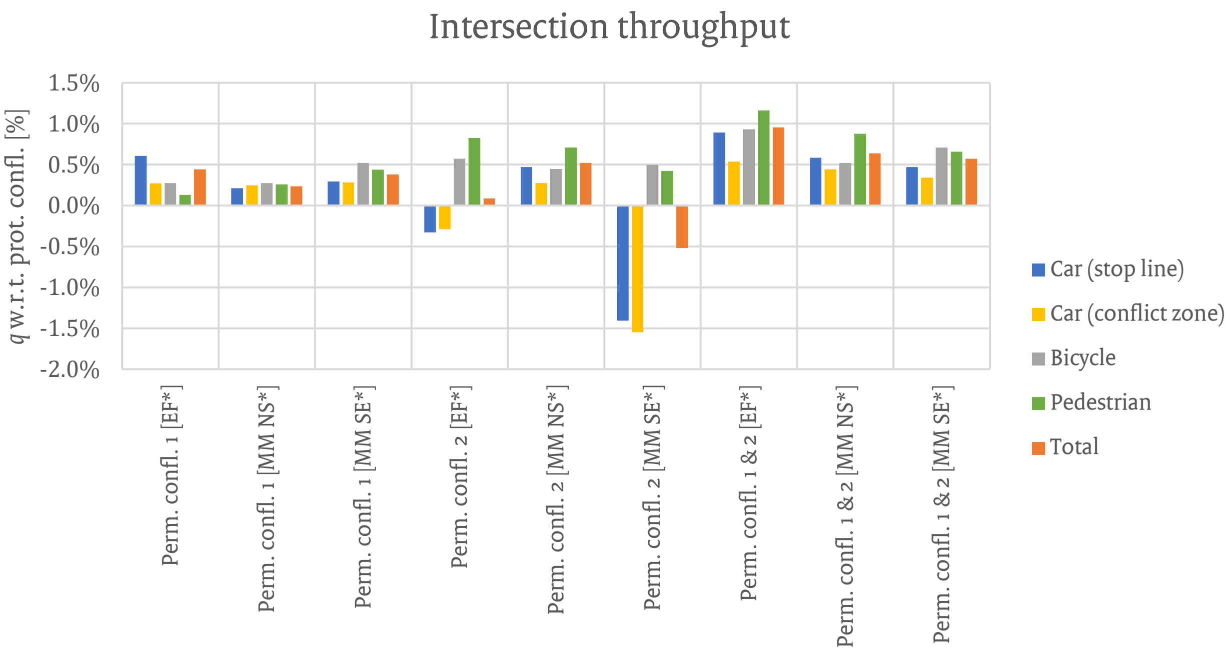


Figure 6-7 | Relative simulation study results for average intersection throughput, given as measured traffic flow volume *q* [veh/h],, per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

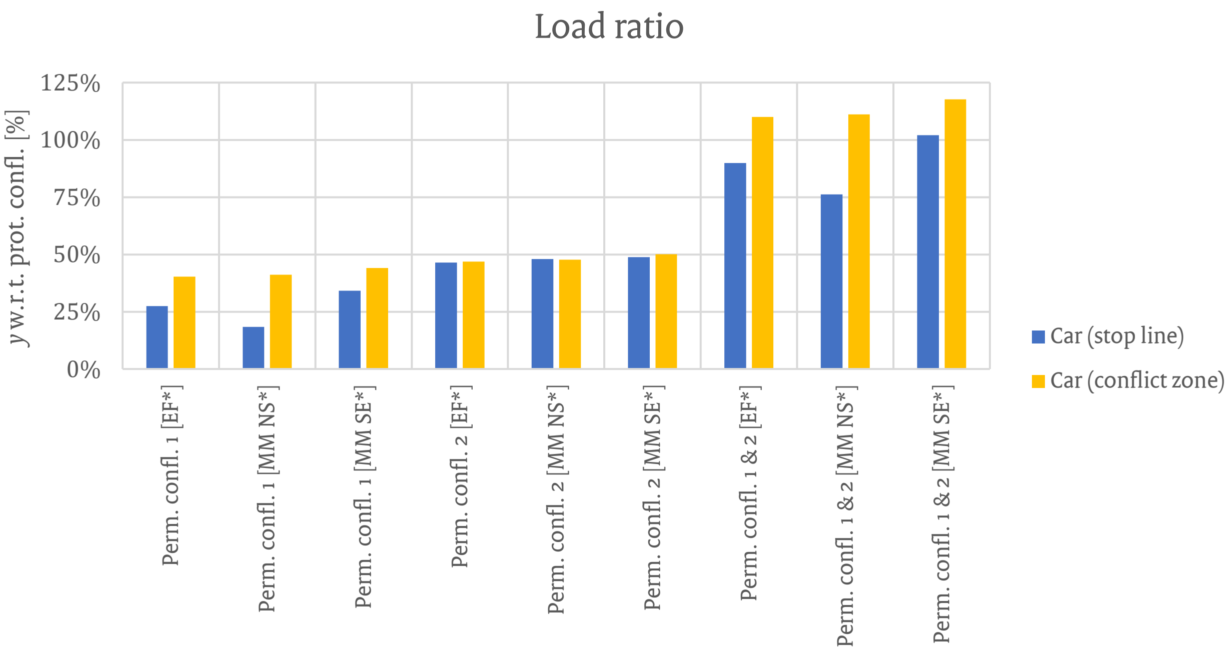


Figure 6-8 | Relative simulation study results for average load ratio *y* [-], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

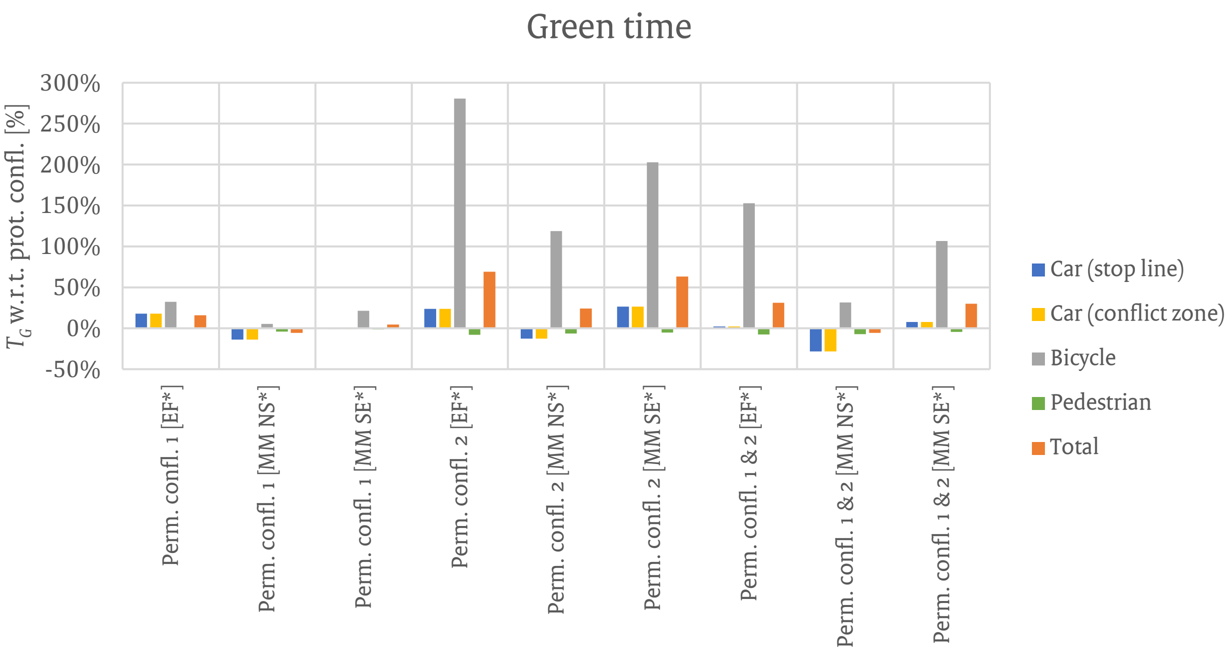


Figure 6-9 | Relative simulation study results for average green time T_G [s], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

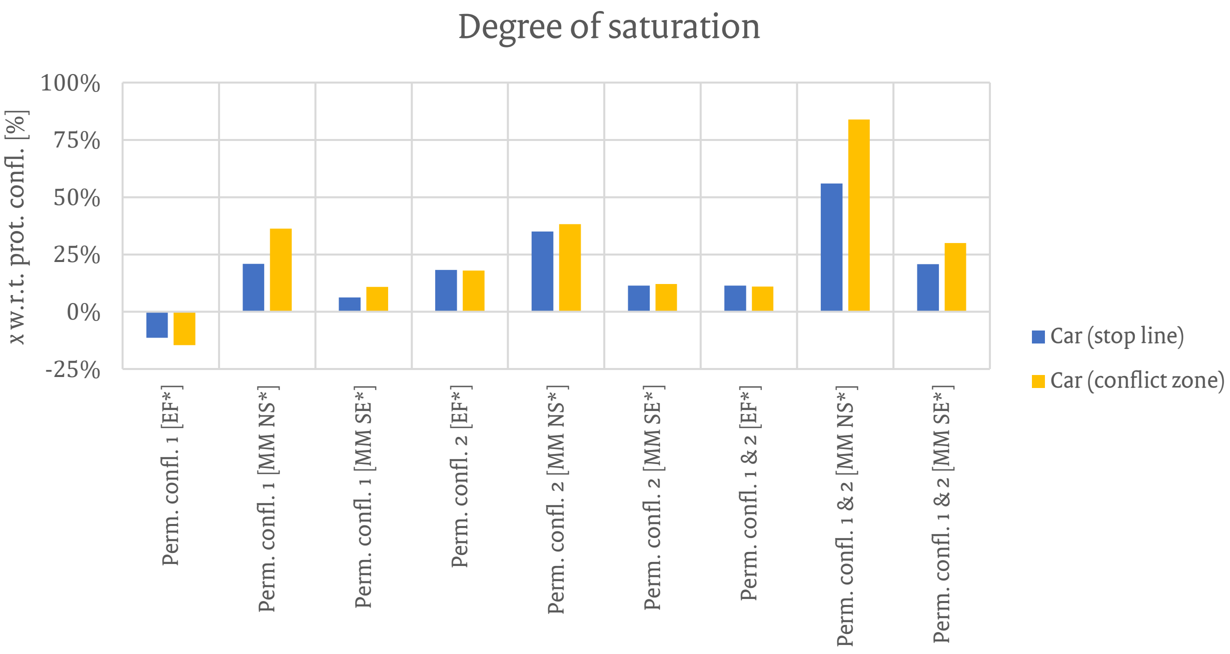


Figure 6-10 | Relative simulation study results for average degree of saturation x [-], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

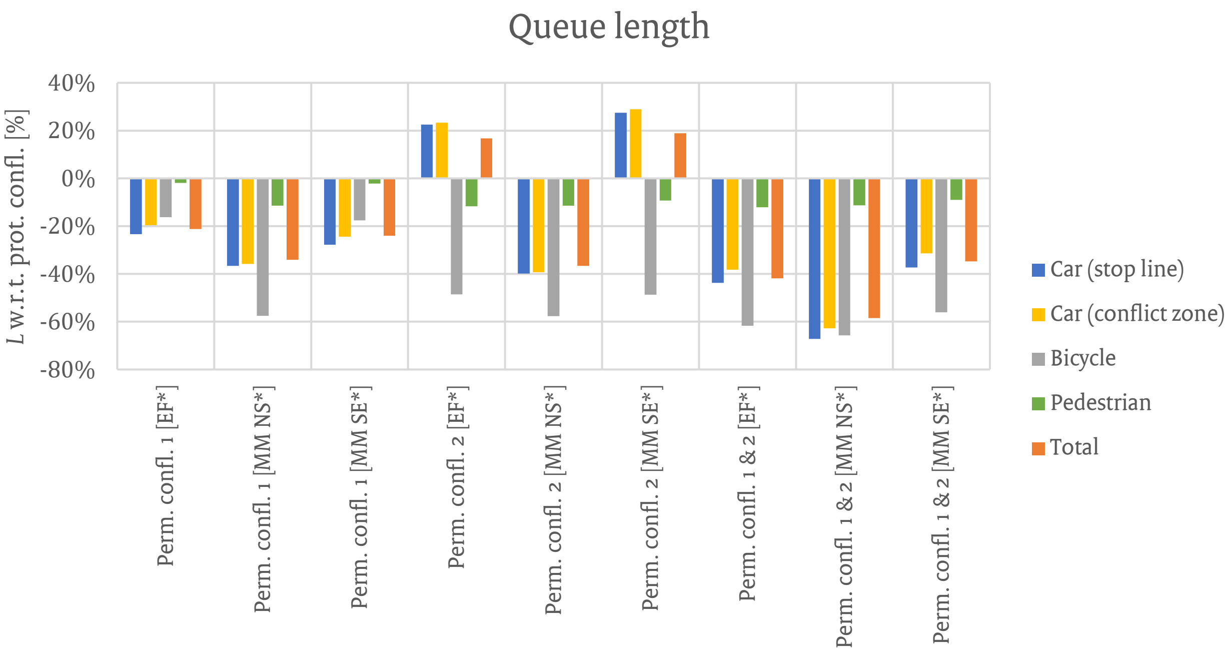


Figure 6-11 | Relative simulation study results for average queue length *L* [m], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.; black dotted line). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

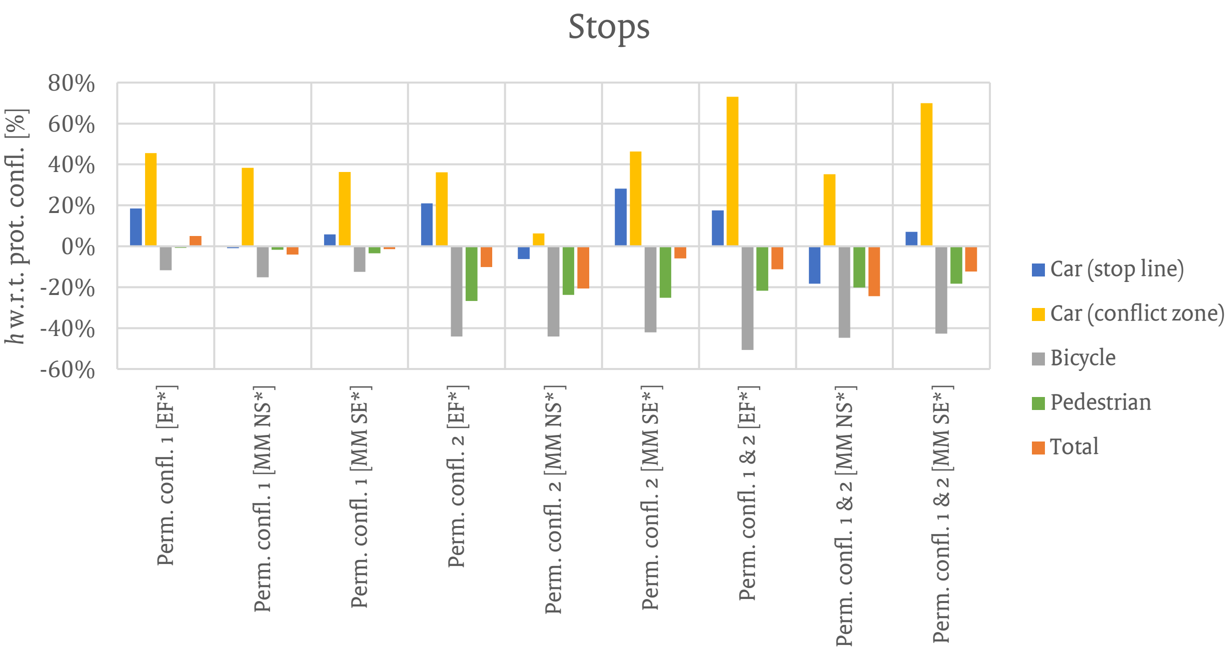


Figure 6-12 | Relative simulation study results for average number of stops *h* [#], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.; black dotted line). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

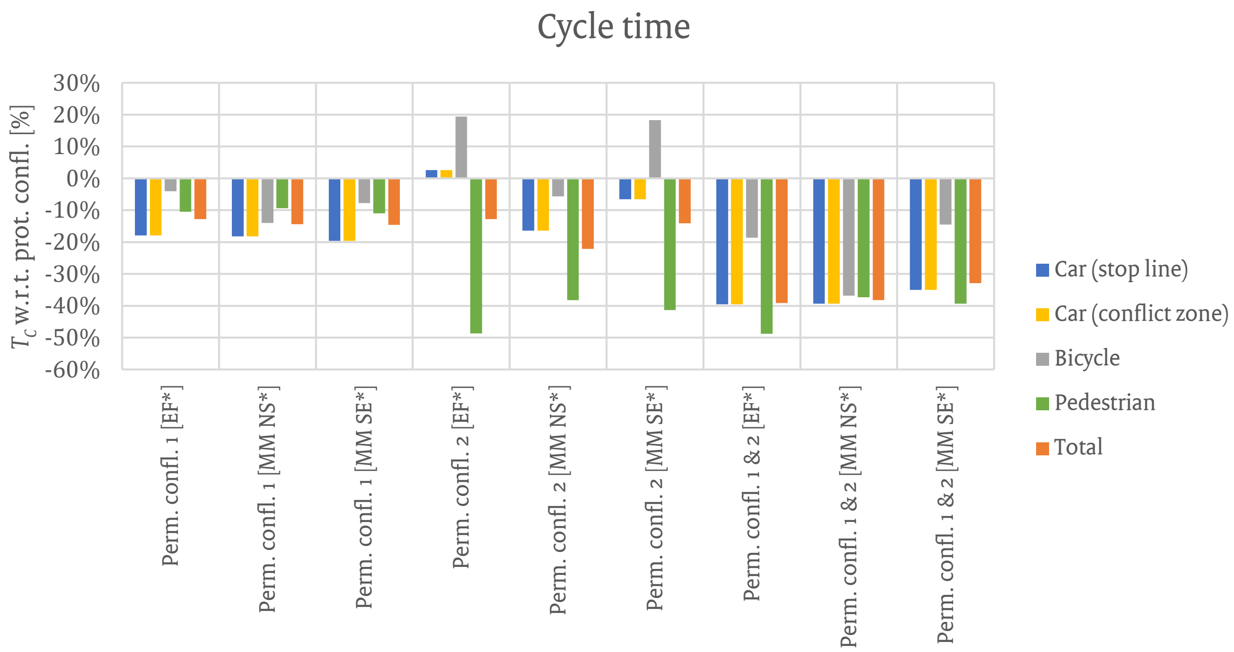


Figure 6-13 | Relative simulation study results for average cycle time T_C [s], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.; black dotted line). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

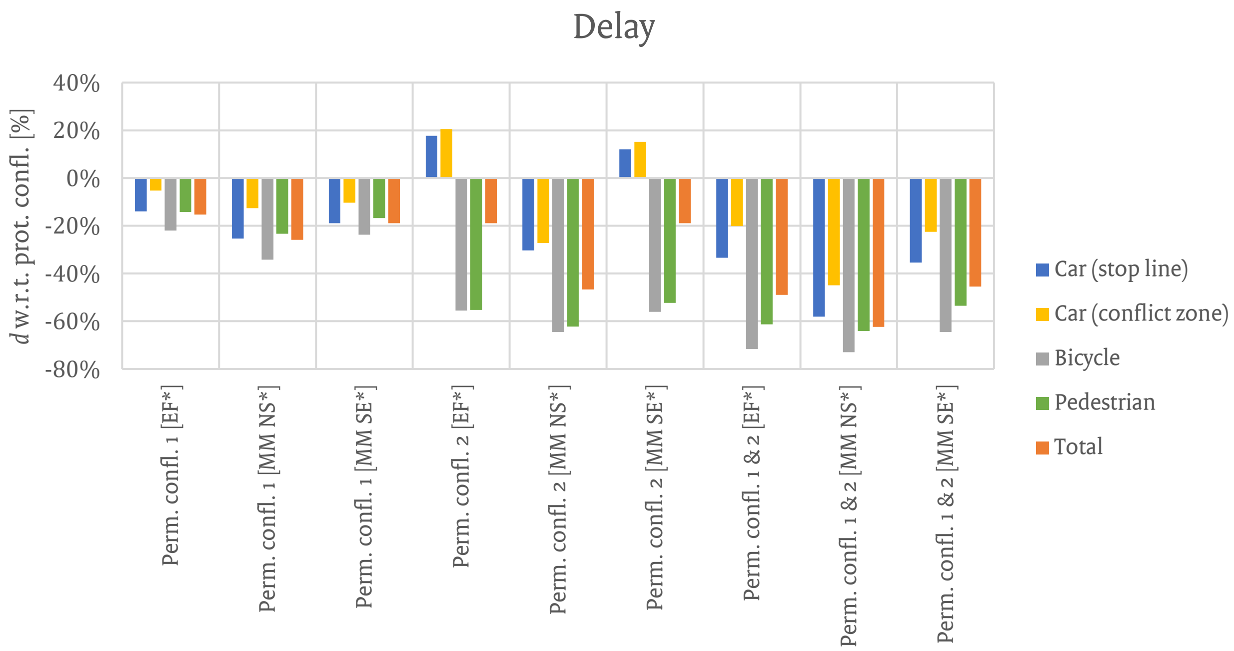


Figure 6-14 | Relative simulation study results for average delay d [s/pce], per permitted conflict (perm. confl.) type, per traffic flow volume scenario, with respect to protected conflicts (= 0%; prot. confl.; black dotted line). *: EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

Lastly, it can be seen that in a more general perspective, the effects for signal groups for cars differ for the location where data is collected – stop line, or conflict zone. That is, when the data that is collected at the conflict zone is considered, the effects are in general larger than for data collected at the stop line.

6.3.2. Queues

Regarding the queues – queue lengths L, and number of stops h – it can be seen that they, on average, decrease, Figure 6-11, and Figure 6-12 on page 52. Indeed, the queue lengths do decrease for all signal groups, except for the car signal groups when permitted conflict type 2 is implemented. This implies a sort of turning point where the effects of permitted conflicts with respect to protected conflicts become unfavourable, as will be discussed more in detail in section 6.3.3. The number of stops is found to only decrease for signal groups with only active modes, thus for cars, the number of stops increased. Again, it can be seen that the consequences are more severe for the signal groups for cars when the data collected at the conflict zone is considered. This also quite logical, in particular regarding the number of stops, because vehicles now might have to stop a second time to yield for crossing traffic in a permitted conflict. When looking at the results per signal group, as given in appendix B, it can be seen that if a car signal group does not have a permitted conflict, the number of stops do decrease: up to 11% less stops are observed. In contrast, it is observed that the number of stops of permissive phasing car signal groups increases with over 40%.

6.3.3. Travel times and delays

As shortly introduced in section 6.4.1, the increase of the degree of saturation is quite limited with respect to the increase of the load ratio, which is the result of the decrease of the cycle time T_C, see Figure 6-13 on the previous page. That is, in only two scenarios for the alternative with only permitted conflict type 2 implemented, the cycle time is found to increase, namely for equal flows, and major-minor flows south-east, in particular for signal groups for bicyclists. Although they increased with 18% to 19%, which might seem as not very severe, the respective absolute values are 110.7 s, and 91.2 s. These absolute cycle times are considered as quite long. However, comparing this to the green time, it is found that the corresponding green times (Figure 6-9 on page 51) have more than doubled, to respectively 54.5 s, and 46.3 s, implying that approximately half of the cycle time is used as green time. Therefore, the high cycle times are concluded to be the result of the increased green times. Because this not a very surprising conclusion (the amber times did not change, and the clearance times did decrease only because several protected conflicts are removed from the matrix), it is recommended for future research to investigate whether the green time is used optimally: what were the headways of vehicles in relation to the green phase termination condition, because if the headway is large, but too small to be detected as a gap (end of queue), the green time is not terminated, and might not be used in the most optimal way.

The delays d, as given in Figure 6-14 on the previous page, show that on average the delays have decreased, ranging from 15% up to 62% less delay (based on the “total” result). However, in the two scenarios equal flows, and major-minor flows south-east, the delays for cars have increased, ranging from 12% to 20% more delay. Nonetheless, for all other alternatives, and scenarios, the delays have indeed decreased with respect to a conflict-free intersection. Still, it must be noted that it can be seen that the consequences are more severe for the signal groups for cars when the data collected at the conflict zone is considered. That is, if the delay increased for cars, they increased more for cars until the edge of the conflict zone. Also, if the delays decreased, they decreased less for cars until the conflict zone.

Furthermore, the results for delay, as well as the results for queue length, show that in two of the nine permitted conflict scenarios, both the delay, and queue length increase, while for the other seven scenarios, reductions are observed. As briefly introduced in section 6.3.2, this implies that there is a turning point at which the traffic flow efficiency effects become negative when implementing permissive phasing as opposed to conflict-free intersections. That is, before that turning point, so to say, the effects of implementing permitted conflicts are positive (i.e. less delay, etc.), while beyond that point the effects are negative (thus longer queues, etc.). This implies that permitted conflicts do not always result in improved traffic flow efficiency effects. Because the only variables in each scenario are (1) the traffic flow volumes, as well as the distribution of these volumes over the signal groups (i.e. equal flows, major-minor flows north-south, or major-minor flows south-east), and (2) the type of permitted conflict implemented, this implies that the turning point is related to these variables. In particular the traffic flow volumes seem to affect the aforementioned turning point, whereas the traffic flow volume is thus related to the permitted conflict type. This means that the turning point denotes the point at which the traffic flow volumes, as well as the distribution of these volumes over the signal groups becomes such that the delays, and queue lengths are approximately equal when permitted conflicts are implemented instead of protected conflicts. Because this is not investigated in this research, it is recommended for future work to investigate whether such a turning point exists, and where this turning point lays.

6.4. Result synthesis: relation to hypotheses

The results show that, in general, the implementation of permitted conflicts has a positive effect in terms of queue lengths, cycle time, and delays. Also, it showed a marginal effect on the intersection throughput, and a negative effect on the saturation flow – and consequently the load ratio, and degree of saturation –, and number of stops. Although in some scenarios, this is found to be not always the case, the overall trend is thus as discussed above. In relation to the hypotheses, as discussed in section 4.4, the conclusions are formulated as explained below, per assessment aspect. In short, of the nine aforementioned hypotheses, a total of six are found to be plausible to be true, two are implausible, and one is considered as indecisive (neither plausible, nor implausible).

6.4.1. Throughput and capacity

The conclusions regarding the hypotheses on *Throughput and capacity* are as listed below:

- The implementation of permitted conflicts was expected to **improve the throughput, and capacity** of a signalised intersection. This is measured as traffic flow volume. The results then show that although the intersection throughput did indeed improve, the results are rather marginal: +1.2% at most, see Figure 6-7. Therefore, the hypothesis is **indecisive**.
- The **saturation flow** was expected to **decrease** as a consequence of the permitted conflicts, because vehicles have to yield to crossing traffic during their green phase. The simulation study results do indeed show that this is the case, quite severe even, namely from 2300 pce/h on a conflict-free intersection to 1200 pce/h with both permitted conflict types 1 and 2 implemented, on average, which is a reduction of almost half (48%). In Figure 6-6, it can even been seen that for some signal groups the reduction was even worse (i.e. reduced with more than 50%). This hypothesis is thus found to be **plausible to be true**.
- As a consequence, it was also expected that the **load ratio increases**. This was also the case, namely with 18% to 118% (depending on the location where the data is collected), see Figure 6-8, thus this hypothesis is **plausible** as well.
- It was expected that the implementation of permitted conflicts would result in an **improved degree of saturation**. That is, a reduced degree of saturation, in which the increased load ratio is counterbalanced by a reduced cycle time. The reduction of the degree of saturation was also expected to be limited due to a reduction of the green time as well. Based on the results presented in Figure 6-10 in which an increase was observed of up to 56% to 84% (depending on the location where the data is collected), this hypothesis on the

degree of saturation is **implausible**, thus not likely to be true, because it was found that in general the degree of saturation increased, to (near-)oversaturated values.

6.4.2. Queues

For the assessment aspect *Queues*, the conclusions on the hypotheses are as follows:

- The **queue lengths** were expected to **decrease** due to the implementation of permitted conflicts. The results show that this is the case, on average, see Figure 6-11: the queue lengths reduced up to 67%, although in two of the nine permitted conflict scenarios the queue length increased up to 29% for car traffic. Therefore, the hypothesis is **plausible**.
- The implementation of permitted conflicts was expected to **increase** the **number of stops of signal groups with permissive phasing**. On the other hand, the **number of stops of signal groups without permissive phasing**, though on a signalised intersection with permitted conflicts, were expected to **decrease**. The latter was expected to suppress the effect of the former. The results in Figure 6-12 show that number of stops of signal groups with permissive phasing did indeed increase (up to 73%), while the number of stops of signal groups without permissive phasing decreased a little (up to 51%, though on average with 10%). The suppressing effect of the latter is found to be fairly limited. Therefore, the overall effect is that, in particular cars, have to stop more often when permitted conflicts are implemented. The hypothesis is thus **implausible**.

6.4.3. Travel times and delays

Regarding *Travel times and delays*, the following conclusions are formulated in relation to the hypotheses:

- It was expected that the implementation of permitted conflicts results in **shorter cycle times**. The simulation study results show that this is the case, in general, see Figure 6-13, because the average cycle time decreased with up to 39%. Therefore, the hypothesis is **plausible**.
- The former hypothesis was based on the assumption that **the fewer the blocks in the block sequence, the shorter the cycle time** becomes. In general, this is also found. That is, in the two-block controller with both permitted conflict types 1 and 2 implemented, the reduction of the cycle time is larger than when three, or four blocks are used, see Figure 6-13. Moreover, the cycle time is also shorter in a three-block controller (permitted conflict type 1) than in a four-block controller (permitted conflict type 2). This is found for all traffic flow volume scenarios. Therefore, this hypothesis is also **plausible**.
- As a consequence, the implementation of permitted conflicts was also expected to **reduce** the **delays**. This was also the case, see Figure 6-14. However, it must be noted that, just as with queue lengths, the delay for car traffic increases with 12% to 20% in two of the nine permitted conflict scenarios. Nonetheless, this hypothesis is **plausible** as well.

6.5. Main findings

The main findings of the simulation study are as enumerated below:

- The objective of the simulation study was to identify how a different conflict handling at a signalised intersection (i.e. permitted conflicts versus protected conflicts) result in a different traffic flow efficiency performance.
- The simulation study uses a synthetic, symmetric signalised intersection, with four approaches. That way, different details in the geometric intersection design are excluded, and the number of identical conflict zones is maximised (i.e., each approach is identical, thus the conflict zones of one approach are identical to those of the other three approaches), thereby reducing the time needed to perform the simulation study as well. The signalised intersection is designed according to the Dutch guidelines. Since the traffic safety conditions, and geometric design elements that are not quantified in these guidelines (e.g. the median width),

the American guidelines are used as well. The signalised intersection includes signal groups for cars, and for active modes, which implies that both permitted conflict types 1, and 2 can be simulated.

- The results show that the type of conflict implemented at the signalised intersection does indeed result in a different performance. Based on the results, six hypotheses of the nine are concluded to be plausibly true, two are implausible, and one is undecisive (nether plausible, nor implausible). In section 6.4, it is stated which hypotheses are plausible, implausible, or indecisive.
- Regarding the saturation flow, it is indeed observed that permitted conflicts reduce the capacity of a signal group during green, because vehicles now have to wait for, and yield to crossing traffic in a permitted conflict, as was expected. The reduction was found to be rather severe, resulting in load ratios that are up to twice as high when permissive phasing considered with respect to a conflict-free intersection. The improved intersection throughput is observed to be too marginal to counterbalance this effect. Consequently, the degree of saturation increased as well, even to (near-)oversaturated conditions.
- The number of stops were found to increase on average. When looking at the results per signal group, it can be seen that in some cases the number of stops decreased. That is, the number of stops of signal groups without permissive phasing, or those signal groups that do not have to yield to crossing traffic, decreased. This was also expected.
- The cycle times are found to decrease as well, whereas the level of cycle time reduction relates to the number of blocks in the block sequence. Although the decreased cycle time limited the increase of the degree of saturation, it was not enough to prevent (near-)oversaturation at the considered signalised intersection. Nonetheless, it did result in less delays, and shorter queues on average, except for two of the nine permitted conflict scenarios.
- The results also show that in two of the nine tested permitted conflict scenarios both the delays, and queue lengths increased. Because the only variables in the tested scenarios are the permitted conflict type, and traffic flow volume, it hypothesised that there might be a turning point at which the traffic flow volumes, as well as the distribution of these volumes over the signal groups, in relation to the permitted conflict type, becomes such that the traffic flow efficiency effects are approximately equal when permissive phasing is implemented with respect to a conflict-free intersection. Before that turning point, so to say, the effects of implementing permitted conflicts are positive (e.g. less delay), while beyond that point, the effects are negative (e.g. more delay). It is recommended for future work to investigate whether this is the case, and how this relation can be quantified.

7. Conclusions and recommendations

In the first chapter of this report, the research objective with corresponding research questions were formulated. These research questions are answered in this chapter. Also, recommendations are given on both further implementation of permitted conflicts, and future work on this topic, and related topics.

7.1. Conclusions

The objective of this research was to identify the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts at vehicle-actuated traffic signal controllers on Dutch signalised intersections, as opposed to the current practice with mainly protected conflicts, given that traffic safety conditions are met, and countermeasures are applied to ensure a safe implementation, by gaining understanding in what the potential consequences of permitted conflicts are for traffic safety and how the potential resulting risks can be reduced, how permitted conflicts affect the traffic flow efficiency, and assessing these traffic flow efficiency effects in a simulation study. This resulted in the following research question: *What are the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts, when compared implementing protected conflicts on signalised intersections?*

To be able to answer this research question, the sub-questions are answered first.

What are permitted conflicts?

A permitted conflict is conflict type at signalised intersection, which allows traffic on streams, or signal groups to meet each other at the conflict zone during their green phase. On the other hand, there are protected conflicts which separate traffic in time. That is, traffic on signal groups with a protected conflict do not meet at the conflict zone during their green phase. In the Swedish guidelines, it is stated explicitly that signal groups that cross each other perpendicularly have to be treated as protected conflicts. A signalised intersection with only protected conflicts is also known as a conflict-free intersection.

Within the domain of permitted conflicts, there are multiple types of permitted conflicts, depending on the modes, and movements involved. In this research, two types are relevant:

1. Parallel car signal groups: a through-going car signal group has a permitted conflict with a left-turning car signal group from the opposite direction;
2. Car signal group with a parallel signal group for active modes: a left-, or right-turning car signal group has a permitted conflict with a parallel through-going signal group for active modes.

In practice, permitted conflicts are widely implemented. That is, they are implemented in various countries, e.g. Belgium, Germany, Austria, the Scandinavian countries, France, Italy, the U.S.A., and China. In all these countries, and in the Netherlands, both types of permitted conflicts are implemented. In European countries, permitted conflict type 2 is more often implemented, especially on urban signalised intersections.

What are the known consequences of permitted conflicts?

The traffic signal controller design consequences of permitted conflicts are that they result in a shorter cycle time, and that for a safe implementation, a separate turning bay is recommended. Also, the lane configuration,

and saturation flow play a role. That is, the more lanes are considered, the more dangerous an intersection becomes, and the saturation flow decreases when permitted conflicts are considered.
Regarding traffic safety, it is concluded that the implementation of permitted conflicts results in a higher crash risk, and thus that protected conflicts result in a safer signalised intersection. To reduce this crash risk, the guidelines state several traffic safety conditions:

- Road users must be able to see each other when they have a permitted conflict to enable them to negotiate their conflict safely according to the priority rules;
- The speeds of the permitted conflict signal groups may not be too high;
- The road users should expect the conflict, which implies a consistent policy on permitted conflicts in the considered (urban) region, and warning signs or lights to alert road users on the permitted conflict(s);
- The geometric road design of the intersection must enable the aforementioned conditions, in addition to being (i) small scale (no more than two lanes on the crossing approaches), (ii) enough space on the intersection for vehicles to wait for their turn, (iii) no blocking of the view while vehicles are waiting, and (iv) the median should not be too wide, which could also block the view;
- The traffic flow volume should not be too large, in order to prevent oversaturation of a permitted conflict signal group;
- A synchronised, or pre-start of signal groups must be implemented, alongside warning sings, or lights, as a way to alert road users of the permitted conflict. The exact countermeasures depend on the type of permitted conflict.

The traffic flow efficiency effects are known to be related to the cycle time. Permissive phasing enables a shorter cycle time, and thus cause less delay. Additionally, it is stated that the reduced delays come at the cost of traffic safety. Furthermore, at signalised intersections with permitted conflicts, in most cases type 1, the delays of both the left-turning traffic, and through-going traffic depend on the traffic flow volumes of these movements. The same goes for queue lengths, and stops. In general, it is found that signalised intersections with protected conflicts have higher delays.

What are the expected traffic flow efficiency effects of permitted conflicts?

The considered performance indicators are relate to the assessment aspects, which are explicitly stated in the research objective. In short, the following assessment aspects, and corresponding performance indicators are used:

- *Throughput and capacity*: (intersection) capacity (in relation to saturation flow as well), load ratio, and degree of saturation;
- *Queues*: queue length, and number of stops;
- *Travel times and delays*: cycle time, and delays.

For each assessment aspect, hypotheses are formulated which describe the expected traffic flow efficiency effects of permitted conflicts with respect to protected conflicts. These expectations are listed in Table 7-1 on the next page. It must be noted that the saturation flow is expected to decrease due to the fact that traffic that now has to yield for crossing traffic, during their green phase. This is expected to also increase the number of stops on these signal groups, while the other signal groups are expected to have fewer stops, resulting in less stops on average. Also, the shorter cycle time is expected to be related to the number of blocks in the block sequence: it is hypothesised that the fewer blocks there are in the block sequence, the shorter the cycle time is. Lastly, although it is expected that permitted conflicts improve the (intersection) throughput and capacity, the literature on gap acceptance models state that the saturation flows are also affected by the critical gap size. This is considered as one of many influential factors.

Table 7-1 | Traffic flow efficiency effect expectations per performance indicator, with increased performance, or value (incr. perf. / value), and a decreased performance, or value (decr. perf. / value).

Assessment aspect	Performance indicator	Expectation
Throughput and capacity	Intersection throughput	Incr. perf. / value
Throughput and capacity	Saturation flow (intersection capacity)	Decr. perf. / value
Throughput and capacity	Load ratio	Incr. perf. / value
Throughput and capacity	Degree of saturation	Decr. perf. / value
Queues	Queue lengths	Decr. perf. / value
Queues	Number of stops (signal groups that have to yield)	Incr. perf. / value
Queues	Number of stops (signal groups that have priority)	Decr. perf. / value
Queues	Number of stops (on average)	Decr. perf. / value
Travel times and delays	Cycle time	Decr. perf. / value
Travel times and delays	Delays	Decr. perf. / value

How can permitted conflicts be simulated?

The literature on analytical gap acceptance models show that most research is done on specific aspects related to permitted conflicts at signalised intersections. That is, because the critical gap size depends on various factors, these factors in particular are investigated. The most often mentioned factors are (i) sight obstruction, (ii) front-of-queue delay, and (iii) permissive phasing with active modes involved.

Based on the findings of a simulation study, and results from literature, it is concluded that the VISSIM simulation model is validated on analytical gap acceptance models. That is, permitted conflicts can be simulated with VISSIM. The simulation study results show that although the critical gap size differs per considered conflict point, the critical gap sizes are similar to those in literature. Therefore, the conclusion is that the simulation model is valid in terms of the used analytical gap acceptance model, in relation to permitted conflicts.

How do permitted conflicts affect the traffic flow efficiency with respect to protected conflicts?

The simulation study results show that the types of conflict implemented at the signalised intersection does indeed result in a different performance. In short, the aforementioned hypotheses are concluded to be plausible, or implausible as listed in Table 7-2 on the next page.

The results also showed that there is indeed a relation between the cycle time, and the number of blocks in the block sequence. That is, the fewer blocks there are in the block sequence, the shorter the cycle time is, except when the green time is very long which limits the reduction of the cycle time, or even leads to an increased cycle time. Regarding the saturation flow, it is indeed observed that permitted conflicts reduce the capacity of a signal group during green, because vehicles now have to wait for, and yield to crossing traffic in a permitted conflict, as was expected. The reduction was found to be rather severe (up to 48% less saturation flow on average, with signal groups with up to 67% less saturation flow), resulting in load ratios that are up to twice as high when permissive phasing considered with respect to a conflict-free intersection. The improved intersection throughput is observed to be too marginal to counterbalance this effect, since it improved the throughput with 1.2% at most, while in some scenarios, the throughput even decreased with as much as 1.5%, hence an indecisive conclusion in Table 7-2. Consequently, the degree of saturation increased as well, even to (near-)oversaturated conditions.

Moreover, it is found that is some cases, the effects of implementing permitted conflicts are negative (e.g. more delay). It is hypothesised that this related to the traffic flow volumes. This implies that the traffic flow volumes affect the degree of impact the implementation of permitted conflicts have as opposed to protected conflicts. That is, there might be a turning point, related to the traffic flow volume with respect to the permitted conflict type, at which the traffic flow efficiency effects of implementing permitted conflicts become negative.

Table 7-2 | Traffic flow efficiency effect expectations and (im)plausible hypotheses per performance indicator, with increased performance, or value (incr. perf. / value), and a decreased performance, or value (decr. perf. / value).

Assessment aspect	Performance indicator	Expectation	Hypothesis
Throughput and capacity	Intersection throughput	Incr. perf. / value	Undecided
Throughput and capacity	Saturation flow (intersection capacity)	Decr. perf. / value	Plausible
Throughput and capacity	Load ratio	Incr. perf. / value	Plausible
Throughput and capacity	Degree of saturation	Decr. perf. / value	Implausible
Queues	Queue lengths	Decr. perf. / value	Plausible
Queues	Number of stops (signal groups that have to yield)	Incr. perf. / value	Plausible
Queues	Number of stops (signal groups that have priority)	Decr. perf. / value	Plausible
Queues	Number of stops (on average)	Decr. perf. / value	Implausible
Travel times and delays	Cycle time	Decr. perf. / value	Plausible
Travel times and delays	Delays	Decr. perf. / value	Plausible

What are the traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts, when compared to implementing protected conflicts on signalised intersections?

The implementation of permitted conflicts at signalised intersections with vehicle-actuated traffic signal controller are found to affect various aspects. Indeed, the traffic flow and accessibility (traffic flow efficiency), traffic safety, and environmental factors are all affected. The main trade-off is showed to be between traffic flow efficiency, and traffic safety: the reduction of the cycle time, delays, and queue lengths, do come at the cost of traffic safety. That is, in literature, it is found that permissive phasing poses traffic safety risks, while this research has proven that permissive phasing results in shorter cycle times, less delays, and shorter queues.

In a broader perspective, it is found that in practice, quite a lot of traffic safety conditions, and countermeasures are in place to reduce, and even mitigate the traffic safety risks, as found in literature. This implies that permitted conflicts can be implemented relatively safely. In other words, even though signalised intersections with permitted conflicts are more unsafe than conflict-free intersections, permitted conflicts can still be implemented. The implementation has its benefits, as shown by this research.

Indeed, the traffic flow inefficiency effects are positive, in terms of throughput and capacity, queues, and travel times and delays. Although the saturation flow decreases relatively severe when permitted conflicts are implemented, the effect on the cycle time, delays, and queue lengths are rather positive. Moreover, for signal groups with priority – i.e. signal groups, with, or without a permitted conflict, but do not have to yield to crossing traffic – the number of stops were found to decrease as well. The used traffic flow volume sets in this research have shown to potentially result in oversaturation, due to the decreased saturation flow. However, it is expected that with other traffic flow volumes, or additional countermeasures in the design of the traffic signal controller, these effects can be reduced. This is especially interesting to consider, given the positive effect on the cycle time, delays, and queue lengths. Thus, it is concluded that, overall, traffic flow inefficiency effects are positive.

Therefore, the conclusion is as follows:

The traffic flow efficiency effects, in terms of intersection throughput and capacity, queues, and travel times and delays, of implementing permitted conflicts, as opposed to implementing protected conflicts on signalised intersections, are positive, in that sense that it resulted in shorter cycle times, less delay, and shorter queues on average. For signal groups with priority, the number of stops also decreased. Although there is a risk of oversaturation, the overall conclusion is that the traffic flow inefficiency effects are positive on average. That is, in some cases, the traffic flow volumes were such that it resulted in the aforementioned risk of oversaturation, and increase of delays, and queue lengths. Also, permitted conflicts still pose traffic safety risks. In short, this comes down to that *fewer* protected conflicts, equals a *higher* traffic safety risk, but also a *more* efficient traffic flow, on average, hence the title of this research: *Less is More: Improved Traffic Flow Efficiency Effects at Vehicle-Actuated Signalised Intersections with Permitted Conflicts as opposed to Protected Conflicts*.

7.2. Recommendations

The conclusion is that "less is more at signalised intersections": fewer protected conflicts, result in more, or better traffic flow efficiency. Although it also introduces traffic safety risks, there are countermeasures available to reduce these risks. Based on this conclusion, recommendations are formulated for further implementation of, and future research of permitted conflicts.

7.2.1. Practical recommendations

As concluded in section 7.1, the implementation of permitted conflicts results in a better traffic flow efficiency performance in terms of shorter cycle times, less delay, shorter queues, and, depending on the considered signal groups, less stops. This implies that from a traffic flow and accessibility point of view, permitted conflicts at signalised intersections are rather beneficial. One may even state in terms of environmental factors related to e.g. delays, queues, and the number of stops, positive effects might be expected. That is, less stops, and shorter queues might be considered as less harmful to the (urban) environment. Therefore, from this perspective as well, one might conclude that permissive phasing is indeed beneficial.

However, there are still traffic safety risks that need to be accounted for. Although the focus of this research was the traffic flow efficiency, the studied literature did show that permitted conflicts pose serious safety risks. The countermeasures that are proposed in these studies, as well as in guidelines, other than switching from permitted conflicts to protected conflicts, are found to be quite effective in reducing these risks. Examples of such countermeasures are a pre- or synchronised start, warning signs, etc. (CROW, 2006). This can also be seen in practice, see section 2.2.

Furthermore, in practice, the choice to implement permitted conflicts might be based on a rather pragmatic motivation. That is, road authorities might implement permitted conflicts because there is not enough space available to design a signalised intersection with protected phasing for car signal groups with active mode signal groups: the geometric intersection design limits the possibilities to design an efficient traffic signal controller. Also, this implies that permitted conflicts might be implemented as a way to reduce the cycle time, and consequently the delay at an intersection, to prevent it exceeding policy constraints set by the road authority.

In the Netherlands, if permitted conflicts are implemented, it is usually done as a permitted conflict between car signal groups with parallel active modes (type 2). The guidelines state that permitted conflicts are allowed, but they are not recommended. This insinuates that permissive phasing is not desired, and should therefore be treated with caution. Although the guidelines are right to state that certain traffic safety conditions are to be met, given the traffic safety risks as found in literature, it is recommended to give more information on the positive effects of permitted conflicts.

Indeed, the positive effects in terms of a better traffic flow efficiency performance are recommended to be stated more clearly. That way, a better informed choice can be made on which type of conflict – protected versus permitted – is to be implemented. Besides, on urban signalised intersections, space is rather scarce, and the speeds are quite low, implying already reduced traffic safety risks. Therefore, it is recommended to take a more open minded approach to permitted conflicts on urban signalised intersections, for the beneficial effects are worthwhile to take into consideration.

In short, the main practical recommendation is to make better informed decisions on which type of conflict – protected versus permitted – is to be implemented. Instead of stating "no, unless …", in all cases, it is recommended to start with "yes, given that …." This implies that certain conditions are to be met. One of these conditions could be that in urbanised areas, "yes, given that …" should be used, while on rural intersections "no, unless …." Furthermore, the conditions stated in the Dutch guidelines are recommended to be specified further, for instance by quantifying them. That way, it can be checked objectively whether or not the conditions are met. Therefore, it is recommended to specify the conditions, and improve the decision-making on permitted conflicts.

7.2.2. Future research

The research objective was to present the traffic flow efficiency effects of permitted conflicts versus protected conflicts. This is investigated using a limited amount of data, for instance, implying that other aspects relevant for this objective are not investigated in this research. Therefore, some recommendations for future work are given, as listed below:

- *Effect on, and of public transport (PT) and trucks*: this research considered only three modes: cars, bicyclists, and pedestrians. In practice, the traffic compositions is way more diverse, for instance with PT, and trucks. The traffic flow efficiency effects of permitted conflicts for PT, and trucks is thus not investigated. Furthermore, a different traffic flow compositions might also influence traffic flow efficiency effects of other modes. For instance, when there are a lot of trucks, the benefits for delay might be lower. Therefore, it is recommended for future research on this matter to also include other modes, in particular PT, and trucks.
- *Practical data*: instead of simulation data, it might also be interesting to use data from a real-life signalised intersection. That way, the human behaviour aspect, in particular in negotiating permitted conflicts, can be investigated more in-depth.
- *Model validation*: consequently to the use of practical data, the validation of the simulation model in VISSIM done in this research is rather limited. By collecting more data of real-life signalised intersections with permitted conflicts, the model validations could made more thorough. Moreover, the use of a simulation model might be obsolete when only practical data is used in future work.
- *Applicability of VISSIM*: in this research, VISSIM is used. However, as introduced in the points listed above, the VISSIM model might need additional calibration to correctly simulate permitted conflicts. This relates to the reduced sight distance in particular, because reduced sight distance is not present in VISSIM. In future work, it is recommended to investigate how this can be accounted for, and how this affects potential blocking.

- *Variations in conflict types*: in this research, the conflicts on the simulated signalised intersections were identical for each approach. In line with this, all the (identical) conflicts were either permitted conflicts, or protected conflicts. In practice, it might be possible that for e.g. two approaches, the conflicts are protected conflicts, while for the other two approaches have permitted conflicts as well, assuming that each pair of approaches consists of approaches that lay on the same street, so to say. That way, an intersection might have both conflict types implemented. This variation of conflicts, which also relates to the geometric intersection design, is expected to affect the results as well. Thus, it is recommended to investigate these variations in future work.
- *Integral assessment*: the objective of this study was limited to mainly include traffic flow efficiency effects. Still, the literature also related to traffic safety effects. Nonetheless, an integral assessment of all aspects (traffic flow efficiency, traffic safety, and environmental effects) is not performed, although some general expectations are formulated. Therefore, it is recommended to perform a more in-depth, and integral assessment of permitted conflicts, thereby including the effects on traffic flow efficiency, traffic safety, and environmental effects altogether. That way, the decision-making process on this matter can be improved even more.
- *Effect of traffic safety countermeasures*: related to the former, it is not investigated what the effects are of the traffic safety risk reducing countermeasures. These countermeasures, or conditions, are assumed as boundary conditions. It might be interesting to investigate how these boundary conditions affect the outcomes of this research. This might introduce that certain countermeasures are contra-productive from a traffic flow efficiency point of view. If that is the case, it can also be investigated how these contra-productive effects can be reduced, or mitigated. This also enables improving decision-making process on the type of conflicts at signalised intersections.
- *Turning point*: this research used only a limited set of traffic flow volumes. Moreover, only one (synthetic, symmetric) signalised intersection is considered. Given this limited scope, it was not possible to identify a turning point: the point at which the benefits of permitted conflicts in terms of traffic flow efficiency become close to zero. At that point, the implementation of permitted conflicts in general might become contra-productive. That is, the traffic safety risks outweigh the traffic flow efficiency benefits, while in other cases, the other way around might be the case. Given the results presented in this report, it is expected that the turning point relates to the traffic flow volumes with respect to the permitted conflict type. More precisely, it is expected that if motorised vehicles have to yield to a high number of e.g. bicyclists, the effects become contra-productive. The traffic flow volume of motorised traffic is expected to play a role as well. Therefore, it is recommended to investigate whether such a turning point exists, and, if so, where it lays.

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A. List of definitions

Active mode	Pedestrians, bicyclists, etc., as a transport mode.
Advanced realisation	Green phase realisations of signal groups in a block preceding the block of the primary realisation. E.g., a signal group (a) with its primary realisation in block (II), has an advanced realisation if signal group (a) receives green in block (I) already. Dutch definition: *vooruit realiseren*.
Alternative realisation	Green phase realisations of signal groups outside the pre-defined block sequence. A signal group (a) receives an alternative realisation if a conflicting, primary signal group (b) in a given block is already served, or has no request, whereas signal group (a) is not a primary signal group in that block (CROW, 2006). E.g., signal group (a) is defined to have a primary realisation in block (I), and conflicting signal group (b) in block (III). If signal group (b) is already served, or has no request in block (III), signal group (a) might receive green in block (III) as well. The green phase of signal group (a) in block (III) – not its primary block – is then an alternative realisation. Dutch definition: *alternatieve realisatie*.
Block sequence	The follow-up of conflicting signal groups, based on the critical conflict group, given as predefined blocks. In vehicle-actuated traffic signal controllers, a block sequence is a basic setting, usually fixed to fit the demand of a given period. In intelligent traffic signal controllers, the block sequence might change cycle to cycle. Also known as phase plan.
COCON	*COherent CONglomeraat van verkeersregeltechnische software*: software package developed by the Dutch company DTV consultants (2017), used to design (fixed time) traffic signal controllers. COCON is quite commonly used in practice in the Netherlands, as part of the design process of a (vehicle-actuated) traffic signal controller, e.g. to design a block sequence.
Delay	Stop delay, plus the time a vehicle loses to brake (deceleration delay) from, and accelerate (acceleration delay) to the desired or free flow speed, or restricted speed (e.g. when driving in a platoon) (CROW, 2006) (Dion, Rakha, & Kang, 2004). Dutch definition: lost time; *verliestijd*.
pce-value	Passenger Car Equivalent value: converted unit for traffic flow volume, which expresses various vehicle classes, and/or modes as passenger cars. More precisely, for each vehicle class, a pce-value exists which represent the number of passenger cars that could pass a given point, or road section at an intersection instead of the given vehicles (bus, truck, etc.) in the time that vehicle uses (CROW, 2006).
Permitted conflict	Conflict between traffic signal groups at a signalised intersection that can have green and/or amber at the same moment. The conflict is solved using the regular traffic rules. Dutch: *deelconflict*.
Primary realisation	Green phase realisations of signal groups within the pre-defined block sequence.

Protected conflict Conflict between traffic signal groups at a signalised intersection that cannot have green and/or amber at the same moment. It is customary that signal groups that cross perpendicularly are signal groups with protected conflicts. A signalised intersection with only protected conflicts is also called a conflict-free intersection. Dutch: *conflictvrij*.

PT Public Transport.

Saturation flow Capacity during the green phase. In other words, the maximum amount of traffic one lane on a signalised intersection can facilitate under given traffic circumstances, including TSC program, road design, and traffic flow composition, if the TSC would give that lane green for one hour (CROW, 2006). Dutch definition: *afrijcapaciteit*.

Stop delay Delay due to standing still (CROW, 2006) (Dion, Rakha, & Kang, 2004). Dutch definition: waiting time; *wachttijd*.

B. Detailed simulation study results

In this appendix, the simulation study results, as discussed in chapter 6, are presented in more detail. First, the results per signal group are given in appendix B.1, followed by the average results per mode in appendix B.2. In both cases, the results are given per traffic flow volume scenario (equal flows, major-minor flows north-south, and major-minor flows south-east), and per assessment aspect (*Throughput and capacity*, *Queues*, and *Travel times and delays*).

The presentation of the results make use of several abbreviations regarding conflict types, and traffic flow volume scenarios, as discussed in chapter 6 as well. For reference purposes, the used abbreviations are as follows, with corresponding explanation:

- *Prot. confl.*: protected conflict;
- *Perm. confl.*: permitted conflict;
- *EF*: equal flows;
- *MM NS*: major-minor flows north-south;
- *MM SE*: major-minor flows south-east.

B.1. Results per signal group

For reference purposes, the saturation flows per signal group, per conflict type, are as given in Table B-1.

Table B-1 | Saturation flow [pce/h] per signal group.

Signal group	Prot. confl. [pce/h]	Perm. confl. 1 [pce/h]	Perm. confl. 2 [pce/h]	Perm. confl. 1 & 2 [pce/h]
02	2439.5	2439.5	1572.5	1574.5
03	2167.3	1257.0	1522.6	833.7
05	2244.2	2244.2	1572.2	1565.0
06	2143.0	1277.8	1528.2	859.3
08	2231.3	2231.3	1581.8	1574.3
09	2249.9	1246.6	1510.9	826.9
11	2313.4	2313.4	1575.7	1576.8
12	2466.9	1248.5	1504.8	818.3

Furthermore, when computed the relative change of e.g. delay of a permitted conflict with respect to a protected conflict, it is assumed that the protected conflict equals 0%.

B.1.1. Equal flows

B.1.1.1. Throughput and capacity

The results of the following performance indicators are presented on the following pages:

- Intersection throughput;
- Load ratio;
- Green time;
- Degree of saturation.

Table B-2 | Intersection throughput [pce/h] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [pce/h]	Perm. confl.1: absolute [pce/h]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [pce/h]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [pce/h]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	398.4	399.7	0.33%	392.7	-1.43%	400.3	0.48%
02 (conflict zone)	200.8	201.4	0.30%	198.8	-1.00%	201.8	0.50%
03 (stop line)	194.5	196.9	1.23%	193.7	-0.41%	195.8	0.67%
03 (conflict zone)	194.4	196.0	0.82%	193.6	-0.41%	195.0	0.31%
05 (stop line)	391.4	394.1	0.69%	390.9	-0.13%	395.4	1.02%
05 (conflict zone)	195.8	196.9	0.56%	195.7	-0.05%	197.2	0.72%
06 (stop line)	193.4	191.8	-0.83%	192.4	-0.52%	194.0	0.31%
06 (conflict zone)	193.4	190.5	-1.50%	192.1	-0.67%	193.3	-0.05%
08 (stop line)	389.1	391.3	0.57%	387.1	-0.51%	392.8	0.95%
08 (conflict zone)	191.3	192.6	0.68%	190.7	-0.31%	193.2	0.99%
09 (stop line)	196.2	197.5	0.66%	196.8	0.31%	197.7	0.76%
09 (conflict zone)	196.0	196.7	0.36%	196.7	0.36%	196.2	0.10%
11 (stop line)	372.1	377.3	1.40%	373.7	0.43%	378.1	1.61%
11 (conflict zone)	184.0	186.1	1.14%	184.0	0.00%	186.3	1.25%
12 (stop line)	192.1	192.7	0.31%	192.3	0.10%	193.9	0.94%
12 (conflict zone)	192.1	191.8	-0.16%	191.7	-0.21%	193.1	0.52%
22	203.0	203.7	0.34%	203.7	0.34%	203.8	0.39%
24	195.5	195.7	0.10%	196.5	0.51%	197.4	0.97%
26	200.8	201.3	0.25%	202.4	0.80%	202.5	0.85%
28	205.4	206.2	0.39%	206.7	0.63%	208.5	1.51%
31	98.3	98.8	0.51%	99.4	1.12%	99.2	0.92%
32	96.8	97.3	0.52%	97.4	0.62%	98.0	1.24%
33	99.5	99.4	-0.10%	100.5	1.01%	100.6	1.11%
34	91.9	92.2	0.33%	92.6	0.76%	93.5	1.74%
35	96.8	96.2	-0.62%	97.5	0.72%	97.3	0.52%
36	97.7	97.7	0.00%	98.1	0.41%	98.0	0.31%
37	93.9	94.2	0.32%	95.2	1.38%	95.9	2.13%
38	98.6	98.7	0.10%	99.2	0.61%	100.0	1.42%

* Protected conflicts equals 0%.

Table B-3 | Load ratio [-] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.163	0.164	0.33%	0.250	52.92%	0.254	55.68%
02 (conflict zone)	0.082	0.083	0.30%	0.126	53.59%	0.128	55.71%
03 (stop line)	0.090	0.157	74.55%	0.127	41.76%	0.235	161.70%
03 (conflict zone)	0.090	0.156	73.84%	0.127	41.76%	0.234	160.76%
05 (stop line)	0.174	0.176	0.69%	0.249	42.56%	0.253	44.86%
05 (conflict zone)	0.087	0.088	0.56%	0.124	42.67%	0.126	44.42%
06 (stop line)	0.090	0.150	66.32%	0.126	39.51%	0.226	150.16%
06 (conflict zone)	0.090	0.149	65.20%	0.126	39.29%	0.225	149.26%
08 (stop line)	0.174	0.175	0.57%	0.245	40.34%	0.250	43.08%
08 (conflict zone)	0.086	0.086	0.68%	0.121	40.62%	0.123	43.14%
09 (stop line)	0.087	0.158	81.68%	0.130	49.37%	0.239	174.17%
09 (conflict zone)	0.087	0.158	81.13%	0.130	49.44%	0.237	172.37%
11 (stop line)	0.161	0.163	1.40%	0.237	47.45%	0.240	49.08%
11 (conflict zone)	0.080	0.080	1.14%	0.117	46.82%	0.118	48.55%
12 (stop line)	0.078	0.154	98.21%	0.128	64.11%	0.237	204.29%
12 (conflict zone)	0.078	0.154	97.28%	0.127	63.59%	0.236	203.04%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

Table B-4 | Green time [s] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	24.2	19.3	-20.25%	28.8	18.99%	18.0	-25.52%
02 (conflict zone)	24.2	19.3	-20.25%	28.8	18.99%	18.0	-25.52%
03 (stop line)	12.3	22.1	79.69%	16.2	32.12%	18.6	51.69%
03 (conflict zone)	12.3	22.1	79.69%	16.2	32.12%	18.6	51.69%
05 (stop line)	24.2	19.7	-18.56%	27.9	15.26%	18.0	-25.68%
05 (conflict zone)	24.2	19.7	-18.56%	27.9	15.26%	18.0	-25.68%
06 (stop line)	10.6	22.1	108.74%	16.8	58.68%	18.2	72.35%
06 (conflict zone)	10.6	22.1	108.74%	16.8	58.68%	18.2	72.35%
08 (stop line)	23.3	18.7	-19.83%	27.1	16.06%	17.5	-24.89%
08 (conflict zone)	23.3	18.7	-19.83%	27.1	16.06%	17.5	-24.89%
09 (stop line)	12.9	23.0	77.45%	16.4	26.34%	18.9	45.83%
09 (conflict zone)	12.9	23.0	77.45%	16.4	26.34%	18.9	45.83%
11 (stop line)	23.2	19.1	-17.86%	26.5	14.06%	17.2	-25.91%
11 (conflict zone)	23.2	19.1	-17.86%	26.5	14.06%	17.2	-25.91%
12 (stop line)	11.2	23.5	110.49%	16.1	43.77%	18.6	66.61%
12 (conflict zone)	11.2	23.5	110.49%	16.1	43.77%	18.6	66.61%
22	12.4	16.8	35.56%	53.7	333.62%	36.1	191.30%
24	15.8	20.9	32.25%	55.5	250.38%	36.8	132.68%
26	12.5	17.8	42.65%	53.6	328.84%	35.7	185.41%
28	16.6	20.3	22.77%	55.3	233.68%	36.1	118.06%
31	9.3	9.3	-0.04%	8.5	-8.55%	8.5	-9.05%
32	9.1	9.0	-0.84%	8.4	-7.35%	8.5	-5.90%
33	9.3	9.1	-1.77%	8.3	-10.88%	8.6	-7.64%
34	9.0	9.0	-0.11%	8.5	-6.17%	8.4	-6.46%
35	9.3	9.4	0.79%	8.5	-8.56%	8.6	-8.20%
36	9.1	8.8	-3.38%	8.7	-5.02%	8.5	-7.17%
37	9.4	9.3	-0.69%	8.5	-9.06%	8.5	-10.08%
38	9.2	9.0	-2.20%	8.4	-8.51%	8.5	-7.29%

* Protected conflicts equals 0%.

Table B-5 | Degree of saturation [-] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.810	0.785	-3.06%	1.006	24.27%	0.961	18.68%
02 (conflict zone)	0.408	0.396	-3.09%	0.509	24.82%	0.484	18.70%
03 (stop line)	0.906	0.705	-22.14%	1.028	13.44%	0.971	7.19%
03 (conflict zone)	0.906	0.702	-22.45%	1.027	13.44%	0.967	6.81%
05 (stop line)	0.881	0.872	-1.05%	1.026	16.42%	0.962	9.21%
05 (conflict zone)	0.441	0.436	-1.17%	0.514	16.51%	0.480	8.88%
06 (stop line)	0.914	0.697	-23.76%	0.982	7.46%	0.941	2.99%
06 (conflict zone)	0.914	0.692	-24.28%	0.980	7.29%	0.938	2.62%
08 (stop line)	0.894	0.860	-3.69%	1.027	14.98%	0.956	7.04%
08 (conflict zone)	0.439	0.424	-3.59%	0.506	15.22%	0.470	7.08%
09 (stop line)	0.843	0.686	-18.69%	1.039	23.16%	0.971	15.10%
09 (conflict zone)	0.842	0.683	-18.93%	1.038	23.22%	0.963	14.34%
11 (stop line)	0.856	0.842	-1.65%	1.032	20.58%	0.958	11.98%
11 (conflict zone)	0.423	0.415	-1.89%	0.508	20.06%	0.472	11.58%
12 (stop line)	0.807	0.681	-15.63%	1.032	27.85%	0.977	21.00%
12 (conflict zone)	0.807	0.678	-16.03%	1.029	27.45%	0.973	20.50%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

B.1.1.2. Queues

The results of the following performance indicators are presented on the following pages:

- Queue length;
- Number of stops.

Table B-6 | Queue length [m] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [m]	Perm. confl.1: absolute [m]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [m]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [m]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	48.1	31.5	-34.39%	68.4	42.29%	20.8	-56.68%
02 (conflict zone)	48.1	31.6	-34.36%	69.1	43.80%	21.5	-55.25%
03 (stop line)	20.0	19.7	-1.70%	20.2	0.82%	17.4	-13.17%
03 (conflict zone)	20.0	24.5	22.08%	20.7	3.17%	23.9	19.43%
05 (stop line)	50.5	32.1	-36.49%	65.9	30.43%	20.2	-60.09%
05 (conflict zone)	50.5	32.1	-36.47%	66.5	31.59%	20.8	-58.73%
06 (stop line)	17.4	19.3	10.82%	21.0	20.27%	16.3	-6.76%
06 (conflict zone)	17.4	24.0	37.67%	21.5	23.48%	22.6	29.65%
08 (stop line)	47.9	29.5	-38.45%	59.6	24.56%	20.6	-56.96%
08 (conflict zone)	47.9	29.5	-38.42%	60.2	25.74%	21.3	-55.59%
09 (stop line)	20.0	19.5	-2.26%	20.4	1.89%	16.0	-20.06%
09 (conflict zone)	20.0	24.5	22.66%	20.9	4.43%	22.7	13.43%
11 (stop line)	41.2	28.8	-30.05%	46.4	12.59%	19.5	-52.74%
11 (conflict zone)	41.3	28.9	-30.02%	47.1	14.10%	20.1	-51.22%
12 (stop line)	17.1	20.7	20.79%	19.3	13.04%	16.8	-1.67%
12 (conflict zone)	17.1	25.6	49.46%	19.9	16.19%	23.2	35.41%
22	3.1	2.7	-13.70%	1.6	-47.45%	1.2	-62.58%
24	3.0	2.5	-15.14%	1.5	-49.00%	1.2	-60.01%
26	3.2	2.7	-16.31%	1.7	-47.90%	1.3	-61.13%
28	3.3	2.6	-19.51%	1.6	-49.63%	1.2	-62.75%
31	3.2	3.1	-0.86%	2.8	-10.84%	2.8	-11.78%
32	3.0	2.9	-2.65%	2.6	-12.55%	2.6	-12.93%
33	3.0	2.9	-2.25%	2.7	-11.86%	2.7	-11.40%
34	3.0	2.9	-2.86%	2.6	-13.26%	2.6	-12.63%
35	3.1	3.0	-1.95%	2.8	-10.69%	2.7	-11.01%
36	3.1	3.1	-0.96%	2.8	-9.83%	2.8	-11.35%
37	2.9	2.8	-1.65%	2.5	-12.47%	2.5	-13.05%
38	3.3	3.2	-1.97%	2.9	-12.13%	2.9	-12.49%

* Protected conflicts equals 0%.

Table B-7 | Stops [#] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [#]	Perm. confl.1: absolute [#]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [#]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [#]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	1.016	0.915	-9.94%	1.428	40.59%	0.923	-9.12%
02 (conflict zone)	1.015	0.912	-10.12%	1.689	66.33%	1.129	11.21%
03 (stop line)	1.064	1.490	40.05%	1.282	20.50%	1.560	46.64%
03 (conflict zone)	1.064	2.061	93.64%	1.364	28.15%	2.483	133.32%
05 (stop line)	1.030	0.930	-9.69%	1.299	26.12%	0.902	-12.45%
05 (conflict zone)	1.026	0.925	-9.82%	1.481	44.37%	1.123	9.43%
06 (stop line)	1.051	1.476	40.49%	1.218	15.87%	1.470	39.87%
06 (conflict zone)	1.052	2.012	91.18%	1.316	25.11%	2.391	127.24%
08 (stop line)	1.021	0.912	-10.67%	1.238	21.27%	0.892	-12.63%
08 (conflict zone)	1.015	0.914	-9.93%	1.434	41.24%	1.090	7.41%
09 (stop line)	1.042	1.494	43.39%	1.138	9.20%	1.450	39.11%
09 (conflict zone)	1.041	2.046	96.60%	1.227	17.84%	2.380	128.65%
11 (stop line)	0.971	0.899	-7.43%	1.163	19.82%	0.907	-6.58%
11 (conflict zone)	0.983	0.895	-8.87%	1.387	41.20%	1.139	15.97%
12 (stop line)	0.994	1.590	59.95%	1.143	15.04%	1.516	52.53%
12 (conflict zone)	0.993	2.157	117.20%	1.253	26.18%	2.435	145.20%
22	1.041	0.936	-10.04%	0.580	-44.25%	0.499	-52.03%
24	0.973	0.870	-10.51%	0.553	-43.16%	0.496	-48.97%
26	1.084	0.927	-14.50%	0.620	-42.79%	0.525	-51.56%
28	1.032	0.910	-11.82%	0.558	-45.95%	0.517	-49.97%
31	0.871	0.859	-1.32%	0.597	-31.38%	0.651	-25.18%
32	0.889	0.926	4.15%	0.686	-22.76%	0.727	-18.21%
33	0.861	0.846	-1.83%	0.580	-32.71%	0.655	-23.91%
34	0.876	0.856	-2.32%	0.651	-25.73%	0.709	-19.09%
35	0.875	0.835	-4.65%	0.623	-28.87%	0.692	-20.96%
36	0.894	0.929	3.89%	0.713	-20.32%	0.719	-19.61%
37	0.879	0.862	-1.84%	0.640	-27.16%	0.660	-24.94%
38	0.875	0.859	-1.89%	0.657	-24.93%	0.681	-22.14%

* Protected conflicts equals 0%.

B.1.1.3. Travel times and delays

The results of the following performance indicators are presented on the following pages:

- Cycle time;
- Delays.

Table B-8 | Cycle time [s] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	120.1	92.5	-22.94%	116.1	-3.30%	68.2	-43.22%
02 (conflict zone)	120.1	92.5	-22.94%	116.1	-3.30%	68.2	-43.22%
03 (stop line)	123.9	99.4	-19.84%	131.0	5.73%	77.0	-37.87%
03 (conflict zone)	123.9	99.4	-19.84%	131.0	5.73%	77.0	-37.87%
05 (stop line)	122.1	97.7	-19.96%	114.9	-5.87%	68.4	-43.97%
05 (conflict zone)	122.1	97.7	-19.96%	114.9	-5.87%	68.4	-43.97%
06 (stop line)	107.0	102.3	-4.32%	130.7	22.23%	75.9	-29.04%
06 (conflict zone)	107.0	102.3	-4.32%	130.7	22.23%	75.9	-29.04%
08 (stop line)	119.6	91.8	-23.23%	113.7	-4.91%	67.2	-43.81%
08 (conflict zone)	119.6	91.8	-23.23%	113.7	-4.91%	67.2	-43.81%
09 (stop line)	125.2	99.4	-20.58%	130.4	4.17%	76.7	-38.78%
09 (conflict zone)	125.2	99.4	-20.58%	130.4	4.17%	76.7	-38.78%
11 (stop line)	123.4	98.3	-20.32%	115.1	-6.73%	68.7	-44.35%
11 (conflict zone)	123.4	98.3	-20.32%	115.1	-6.73%	68.7	-44.35%
12 (stop line)	115.9	103.8	-10.40%	129.8	12.01%	76.8	-33.75%
12 (conflict zone)	115.9	103.8	-10.40%	129.8	12.01%	76.8	-33.75%
22	89.6	86.4	-3.51%	109.0	21.66%	74.9	-16.38%
24	89.0	88.6	-0.39%	109.8	23.44%	75.7	-14.94%
26	92.7	89.3	-3.58%	112.0	20.91%	75.8	-18.21%
28	99.6	91.5	-8.13%	111.9	12.38%	75.5	-24.19%
31	90.4	83.5	-7.67%	48.5	-46.38%	47.2	-47.80%
32	91.6	84.2	-8.04%	46.3	-49.39%	46.4	-49.29%
33	87.8	79.6	-9.33%	44.7	-49.06%	47.6	-45.73%
34	88.4	80.7	-8.65%	45.3	-48.76%	47.2	-46.63%
35	93.3	82.7	-11.36%	49.1	-47.38%	48.0	-48.58%
36	96.5	83.0	-13.99%	49.8	-48.42%	48.5	-49.78%
37	93.5	83.1	-11.10%	47.9	-48.78%	47.0	-49.68%
38	98.8	86.2	-12.75%	47.9	-51.49%	47.2	-52.22%

* Protected conflicts equals 0%.

Table B-9 | Delay [s/pce] per signal group, for equal flows.

Signal group	Prot. confl.: absolute [s/pce]	Perm. confl.1: absolute [s/pce]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s/pce]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s/pce]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	57.5	42.0	-27.07%	76.0	32.02%	30.2	-47.58%
02 (conflict zone)	57.3	41.6	-27.31%	77.0	34.34%	31.8	-44.52%
03 (stop line)	62.6	58.0	-7.29%	75.3	20.32%	49.0	-21.76%
03 (conflict zone)	62.7	68.4	9.00%	76.9	22.59%	62.3	-0.64%
05 (stop line)	60.3	43.4	-28.01%	69.8	15.66%	29.7	-50.77%
05 (conflict zone)	60.2	42.6	-29.29%	71.2	18.20%	31.6	-47.62%
06 (stop line)	55.6	56.7	1.82%	71.0	27.61%	46.2	-17.03%
06 (conflict zone)	55.8	66.3	18.82%	72.8	30.40%	59.3	6.17%
08 (stop line)	57.2	40.6	-29.14%	64.9	13.40%	30.5	-46.81%
08 (conflict zone)	56.6	40.6	-28.29%	66.5	17.37%	31.7	-44.10%
09 (stop line)	60.9	56.6	-6.97%	67.4	10.63%	45.3	-25.63%
09 (conflict zone)	61.0	67.4	10.44%	69.1	13.24%	58.9	-3.57%
11 (stop line)	55.4	41.8	-24.61%	59.0	6.54%	30.3	-45.28%
11 (conflict zone)	54.8	41.6	-24.14%	59.9	9.28%	32.7	-40.44%
12 (stop line)	55.0	60.8	10.60%	63.2	14.95%	48.5	-11.83%
12 (conflict zone)	55.0	71.1	29.24%	65.0	18.19%	62.4	13.47%
22	34.3	29.1	-15.31%	16.6	-51.73%	9.9	-71.25%
24	34.3	26.2	-23.50%	14.7	-57.14%	10.0	-70.97%
26	37.2	28.4	-23.68%	16.5	-55.54%	10.7	-71.25%
28	36.5	27.3	-25.19%	15.4	-57.78%	9.9	-72.86%
31	38.3	35.1	-8.41%	18.3	-52.08%	15.4	-59.66%
32	41.2	34.1	-17.24%	18.4	-55.46%	15.6	-62.12%
33	38.2	32.9	-13.96%	15.9	-58.51%	15.8	-58.63%
34	42.6	33.8	-20.53%	16.4	-61.54%	15.1	-64.64%
35	39.1	33.4	-14.46%	18.4	-52.90%	15.7	-59.83%
36	39.4	35.6	-9.54%	20.4	-48.22%	16.3	-58.65%
37	40.2	35.3	-12.20%	18.1	-55.03%	14.6	-63.71%
38	43.3	36.2	-16.24%	18.3	-57.79%	16.2	-62.62%

* Protected conflicts equals 0%.

B.1.2. Major-minor flows north-south

B.1.2.1. Throughput and capacity

The results of the following performance indicators are presented on the following pages:

- Intersection throughput;
- Load ratio;
- Green time;
- Degree of saturation.

Table B-10 | Intersection throughput [pce/h] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [pce/h]	Perm. confl.1: absolute [pce/h]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [pce/h]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [pce/h]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	498.6	498.1	-0.10%	501.4	0.56%	501.9	0.66%
02 (conflict zone)	97.7	97.6	-0.10%	98.0	0.31%	98.4	0.72%
03 (stop line)	98.9	98.9	0.00%	99.1	0.20%	99.3	0.40%
03 (conflict zone)	98.9	98.9	0.00%	98.7	-0.20%	99.1	0.20%
05 (stop line)	193.4	194.8	0.72%	193.6	0.10%	194.7	0.67%
05 (conflict zone)	94.6	95.3	0.74%	94.6	0.00%	95.1	0.53%
06 (stop line)	98.4	99.1	0.71%	99.0	0.61%	99.1	0.71%
06 (conflict zone)	98.2	98.7	0.51%	99.0	0.81%	98.7	0.51%
08 (stop line)	490.9	491.2	0.06%	494.6	0.75%	494.0	0.63%
08 (conflict zone)	94.5	94.5	0.00%	95.0	0.53%	94.9	0.42%
09 (stop line)	99.5	99.3	-0.20%	99.5	0.00%	99.6	0.10%
09 (conflict zone)	99.5	99.1	-0.40%	99.2	-0.30%	99.4	-0.10%
11 (stop line)	184.7	186.1	0.76%	185.1	0.22%	185.7	0.54%
11 (conflict zone)	88.2	89.2	1.13%	88.7	0.57%	89.1	1.02%
12 (stop line)	97.5	98.1	0.62%	97.9	0.41%	97.9	0.41%
12 (conflict zone)	97.4	97.6	0.21%	97.9	0.51%	97.7	0.31%
22	203.3	203.8	0.25%	203.4	0.05%	204.3	0.49%
24	196.0	196.6	0.31%	197.6	0.82%	197.6	0.82%
26	202.1	202.0	-0.05%	202.0	-0.05%	202.2	0.05%
28	206.9	208.1	0.58%	208.9	0.97%	208.4	0.72%
31	98.6	99.0	0.41%	99.1	0.51%	99.7	1.12%
32	97.5	97.6	0.10%	97.7	0.21%	98.1	0.62%
33	100.0	100.2	0.20%	100.8	0.80%	100.6	0.60%
34	92.1	93.1	1.09%	93.6	1.63%	93.5	1.52%
35	97.4	97.0	-0.41%	97.2	-0.21%	97.7	0.31%
36	98.1	98.0	-0.10%	98.0	-0.10%	98.5	0.41%
37	94.5	95.1	0.63%	96.3	1.90%	96.1	1.69%
38	99.0	99.2	0.20%	100.0	1.01%	99.8	0.81%

* Protected conflicts equals 0%.

Table B-11 | Load ratio [-] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.204	0.204	-0.10%	0.319	56.01%	0.319	55.96%
02 (conflict zone)	0.040	0.040	-0.10%	0.062	55.61%	0.062	56.05%
03 (stop line)	0.046	0.079	72.42%	0.065	42.63%	0.119	161.01%
03 (conflict zone)	0.046	0.079	72.42%	0.065	42.05%	0.119	160.49%
05 (stop line)	0.086	0.087	0.72%	0.123	42.89%	0.124	44.36%
05 (conflict zone)	0.042	0.042	0.74%	0.060	42.74%	0.061	44.16%
06 (stop line)	0.046	0.078	68.90%	0.065	41.09%	0.115	151.16%
06 (conflict zone)	0.046	0.077	68.56%	0.065	41.37%	0.115	150.66%
08 (stop line)	0.220	0.220	0.06%	0.313	42.12%	0.314	42.63%
08 (conflict zone)	0.042	0.042	0.00%	0.060	41.81%	0.060	42.33%
09 (stop line)	0.044	0.080	80.12%	0.066	48.91%	0.120	172.36%
09 (conflict zone)	0.044	0.079	79.76%	0.066	48.46%	0.120	171.82%
11 (stop line)	0.080	0.080	0.76%	0.117	47.14%	0.118	47.51%
11 (conflict zone)	0.038	0.039	1.13%	0.056	47.65%	0.057	48.21%
12 (stop line)	0.040	0.079	98.81%	0.065	64.61%	0.120	202.70%
12 (conflict zone)	0.039	0.078	97.99%	0.065	64.78%	0.119	202.39%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

Table B-12 | Green time [s] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	20.6	15.8	-23.28%	16.8	-18.32%	12.1	-41.22%
02 (conflict zone)	20.6	15.8	-23.28%	16.8	-18.32%	12.1	-41.22%
03 (stop line)	7.0	7.2	3.13%	6.3	-8.87%	5.9	-15.21%
03 (conflict zone)	7.0	7.2	3.13%	6.3	-8.87%	5.9	-15.21%
05 (stop line)	9.2	7.4	-19.87%	8.5	-7.12%	6.9	-25.13%
05 (conflict zone)	9.2	7.4	-19.87%	8.5	-7.12%	6.9	-25.13%
06 (stop line)	6.3	6.3	-0.30%	6.2	-0.91%	5.7	-8.55%
06 (conflict zone)	6.3	6.3	-0.30%	6.2	-0.91%	5.7	-8.55%
08 (stop line)	20.0	16.0	-19.80%	16.1	-19.23%	12.0	-40.15%
08 (conflict zone)	20.0	16.0	-19.80%	16.1	-19.23%	12.0	-40.15%
09 (stop line)	7.0	7.3	5.37%	6.2	-10.83%	6.0	-14.13%
09 (conflict zone)	7.0	7.3	5.37%	6.2	-10.83%	6.0	-14.13%
11 (stop line)	8.9	7.1	-20.48%	8.2	-7.80%	6.8	-23.40%
11 (conflict zone)	8.9	7.1	-20.48%	8.2	-7.80%	6.8	-23.40%
12 (stop line)	6.4	6.3	-0.99%	6.1	-3.94%	5.7	-9.71%
12 (conflict zone)	6.4	6.3	-0.99%	6.1	-3.94%	5.7	-9.71%
22	11.8	13.4	14.30%	25.3	115.14%	15.0	27.21%
24	16.2	15.7	-3.22%	35.7	120.44%	21.7	33.98%
26	11.9	13.6	14.55%	25.1	111.14%	15.0	26.13%
28	15.9	16.0	1.12%	35.8	125.33%	21.6	36.23%
31	9.0	8.9	-1.37%	8.5	-6.34%	8.5	-5.62%
32	8.7	8.3	-4.39%	8.5	-1.72%	8.4	-3.19%
33	9.2	8.8	-4.62%	8.3	-10.35%	8.1	-12.44%
34	8.8	8.2	-7.06%	8.2	-6.88%	8.2	-7.31%
35	9.0	9.0	-0.39%	8.5	-5.95%	8.5	-6.03%
36	8.6	8.3	-3.92%	8.5	-1.41%	8.3	-4.16%
37	9.2	8.9	-3.13%	8.2	-10.37%	8.3	-9.51%
38	8.9	8.2	-7.39%	8.2	-7.77%	8.1	-8.61%

* Protected conflicts equals 0%.

Table B-13 | Degree of saturation [-] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.821	0.795	-3.22%	1.164	41.80%	1.030	25.43%
02 (conflict zone)	0.161	0.156	-3.23%	0.228	41.44%	0.202	25.50%
03 (stop line)	0.631	0.933	47.84%	0.900	42.70%	1.340	112.48%
03 (conflict zone)	0.631	0.933	47.84%	0.897	42.12%	1.338	112.05%
05 (stop line)	0.830	0.775	-6.66%	0.993	19.63%	0.797	-3.94%
05 (conflict zone)	0.406	0.379	-6.65%	0.485	19.50%	0.389	-4.08%
06 (stop line)	0.679	1.043	53.48%	0.890	31.00%	1.382	103.49%
06 (conflict zone)	0.678	1.038	53.17%	0.890	31.26%	1.377	103.08%
08 (stop line)	0.915	0.870	-4.90%	1.167	27.56%	1.025	12.07%
08 (conflict zone)	0.176	0.167	-4.95%	0.224	27.27%	0.197	11.83%
09 (stop line)	0.615	0.873	41.97%	0.892	45.11%	1.338	117.67%
09 (conflict zone)	0.615	0.871	41.68%	0.889	44.67%	1.335	117.23%
11 (stop line)	0.780	0.755	-3.21%	0.969	24.23%	0.752	-3.49%
11 (conflict zone)	0.372	0.362	-2.85%	0.464	24.67%	0.361	-3.03%
12 (stop line)	0.587	1.039	76.91%	0.935	59.17%	1.468	150.01%
12 (conflict zone)	0.587	1.033	76.19%	0.935	59.34%	1.465	149.76%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

B.1.2.2. Queues

The results of the following performance indicators are presented on the following pages:

- Queue length;
- Number of stops.

Table B-14 | Queue length [m] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [m]	Perm. confl.1: absolute [m]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [m]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [m]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	33.8	19.6	-41.88%	19.3	-42.92%	9.9	-70.73%
02 (conflict zone)	33.8	19.8	-41.30%	19.5	-42.41%	10.1	-70.13%
03 (stop line)	6.5	4.3	-33.48%	3.6	-45.27%	2.6	-60.41%
03 (conflict zone)	6.5	4.5	-31.54%	3.7	-43.34%	5.8	-11.45%
05 (stop line)	13.1	8.7	-33.50%	8.3	-36.81%	4.6	-65.17%
05 (conflict zone)	13.2	9.0	-31.36%	8.6	-34.77%	4.8	-63.38%
06 (stop line)	6.0	4.5	-25.17%	4.3	-29.15%	2.6	-57.44%
06 (conflict zone)	6.0	4.7	-21.35%	4.5	-24.98%	4.1	-32.13%
08 (stop line)	35.1	20.8	-40.81%	19.9	-43.26%	9.5	-72.85%
08 (conflict zone)	35.2	21.0	-40.34%	20.1	-42.85%	9.8	-72.25%
09 (stop line)	6.3	4.6	-27.08%	3.7	-41.37%	2.7	-57.72%
09 (conflict zone)	6.3	4.8	-24.62%	3.9	-38.75%	6.0	-5.11%
11 (stop line)	11.9	8.4	-29.29%	8.1	-32.38%	4.5	-62.41%
11 (conflict zone)	12.0	8.7	-27.02%	8.3	-30.49%	4.8	-59.99%
12 (stop line)	6.1	4.4	-27.68%	4.3	-28.60%	2.7	-55.82%
12 (conflict zone)	6.1	4.6	-24.46%	4.5	-25.50%	4.2	-30.32%
22	2.5	1.3	-48.70%	1.3	-48.70%	1.0	-58.55%
24	2.2	0.7	-68.80%	0.7	-69.02%	0.6	-74.62%
26	2.5	1.3	-45.83%	1.3	-46.75%	1.1	-56.59%
28	2.3	0.7	-68.78%	0.8	-67.86%	0.6	-74.19%
31	3.0	2.8	-8.28%	2.7	-8.94%	2.8	-8.48%
32	2.8	2.5	-10.97%	2.6	-9.86%	2.6	-9.71%
33	2.9	2.5	-13.31%	2.5	-13.56%	2.5	-13.89%
34	2.8	2.4	-13.44%	2.4	-14.20%	2.4	-13.71%
35	2.9	2.7	-8.37%	2.7	-8.48%	2.7	-8.62%
36	3.0	2.7	-9.48%	2.7	-10.18%	2.7	-10.01%
37	2.7	2.4	-13.62%	2.4	-13.30%	2.4	-13.47%
38	3.1	2.7	-14.07%	2.7	-12.68%	2.7	-12.96%

* Protected conflicts equals 0%.

Table B-15 | Stops [#] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [#]	Perm. confl.1: absolute [#]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [#]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [#]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.896	0.816	-8.86%	0.816	-8.87%	0.668	-25.42%
02 (conflict zone)	0.893	0.832	-6.76%	0.948	6.20%	0.835	-6.48%
03 (stop line)	0.942	1.002	6.42%	0.856	-9.14%	0.809	-14.10%
03 (conflict zone)	0.942	1.900	101.63%	0.893	-5.20%	1.720	82.59%
05 (stop line)	0.916	0.859	-6.19%	0.873	-4.70%	0.713	-22.14%
05 (conflict zone)	0.906	0.857	-5.36%	1.086	19.89%	0.877	-3.12%
06 (stop line)	0.888	0.919	3.46%	0.863	-2.81%	0.768	-13.52%
06 (conflict zone)	0.888	1.438	61.99%	0.950	7.04%	1.423	60.29%
08 (stop line)	0.918	0.821	-10.59%	0.833	-9.24%	0.648	-29.37%
08 (conflict zone)	0.934	0.825	-11.69%	0.968	3.59%	0.765	-18.09%
09 (stop line)	0.951	1.005	5.69%	0.878	-7.67%	0.813	-14.52%
09 (conflict zone)	0.950	1.906	100.62%	0.922	-2.92%	1.775	86.79%
11 (stop line)	0.886	0.842	-5.00%	0.867	-2.14%	0.741	-16.40%
11 (conflict zone)	0.878	0.835	-4.93%	1.058	20.44%	0.972	10.69%
12 (stop line)	0.905	0.965	6.68%	0.854	-5.61%	0.809	-10.56%
12 (conflict zone)	0.906	1.495	65.07%	0.926	2.25%	1.495	65.07%
22	0.932	0.788	-15.41%	0.576	-38.24%	0.575	-38.29%
24	0.831	0.690	-16.93%	0.393	-52.63%	0.380	-54.20%
26	0.917	0.808	-11.89%	0.609	-33.60%	0.590	-35.68%
28	0.850	0.706	-16.86%	0.397	-53.27%	0.407	-52.14%
31	0.846	0.821	-2.98%	0.708	-16.30%	0.732	-13.48%
32	0.853	0.865	1.44%	0.718	-15.76%	0.758	-11.14%
33	0.831	0.822	-0.98%	0.562	-32.37%	0.612	-26.26%
34	0.844	0.823	-2.49%	0.591	-30.00%	0.602	-28.66%
35	0.837	0.822	-1.76%	0.692	-17.31%	0.712	-14.90%
36	0.852	0.868	1.89%	0.716	-16.00%	0.732	-14.08%
37	0.825	0.777	-5.73%	0.547	-33.69%	0.599	-27.41%
38	0.830	0.801	-3.49%	0.588	-29.15%	0.610	-26.49%

* Protected conflicts equals 0%.

B.1.2.3. Travel times and delays

The results of the following performance indicators are presented on the following pages:

- Cycle time;
- Delays.

Table B-16 | Cycle time [s] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	82.9	61.6	-25.68%	61.5	-25.76%	39.2	-52.72%
02 (conflict zone)	82.9	61.6	-25.68%	61.5	-25.76%	39.2	-52.72%
03 (stop line)	96.2	85.0	-11.57%	87.7	-8.83%	66.4	-30.98%
03 (conflict zone)	96.2	85.0	-11.57%	87.7	-8.83%	66.4	-30.98%
05 (stop line)	88.6	65.8	-25.75%	68.9	-22.24%	44.1	-50.18%
05 (conflict zone)	88.6	65.8	-25.75%	68.9	-22.24%	44.1	-50.18%
06 (stop line)	93.0	84.3	-9.41%	85.6	-8.00%	68.9	-25.91%
06 (conflict zone)	93.0	84.3	-9.41%	85.6	-8.00%	68.9	-25.91%
08 (stop line)	83.0	63.3	-23.77%	60.2	-27.51%	39.1	-52.97%
08 (conflict zone)	83.0	63.3	-23.77%	60.2	-27.51%	39.1	-52.97%
09 (stop line)	96.7	80.3	-16.95%	84.1	-13.11%	66.4	-31.37%
09 (conflict zone)	96.7	80.3	-16.95%	84.1	-13.11%	66.4	-31.37%
11 (stop line)	86.7	66.2	-23.61%	67.5	-22.15%	43.4	-49.88%
11 (conflict zone)	86.7	66.2	-23.61%	67.5	-22.15%	43.4	-49.88%
12 (stop line)	94.6	83.3	-11.89%	87.8	-7.11%	70.5	-25.43%
12 (conflict zone)	94.6	83.3	-11.89%	87.8	-7.11%	70.5	-25.43%
22	64.0	59.2	-7.56%	62.0	-3.09%	41.8	-34.70%
24	66.6	52.5	-21.21%	63.0	-5.49%	41.8	-37.20%
26	65.5	61.6	-5.90%	62.8	-4.04%	42.1	-35.64%
28	69.4	55.0	-20.79%	62.6	-9.70%	41.8	-39.70%
31	65.2	62.7	-3.89%	44.6	-31.56%	44.8	-31.35%
32	66.0	64.2	-2.64%	43.6	-33.82%	44.8	-32.08%
33	64.2	55.2	-14.02%	37.5	-41.61%	37.5	-41.63%
34	64.6	56.7	-12.30%	37.1	-42.63%	38.0	-41.20%
35	67.3	63.1	-6.24%	45.4	-32.46%	45.3	-32.70%
36	68.6	64.3	-6.37%	46.1	-32.87%	45.6	-33.49%
37	65.5	56.2	-14.14%	36.7	-43.95%	38.1	-41.84%
38	69.1	58.6	-15.26%	36.7	-46.91%	38.4	-44.39%

* Protected conflicts equals 0%.

Table B-17 | Delay [s/pce] per signal group, for major-minor flows north-south.

Signal group	Prot. confl.: absolute [s/pce]	Perm. confl.1: absolute [s/pce]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s/pce]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s/pce]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	35.5	24.5	-31.02%	22.8	-35.82%	13.1	-62.94%
02 (conflict zone)	34.8	25.0	-28.12%	24.0	-31.19%	14.5	-58.36%
03 (stop line)	43.5	32.2	-25.99%	29.0	-33.35%	18.0	-58.59%
03 (conflict zone)	43.9	47.6	8.29%	30.3	-30.99%	29.7	-32.29%
05 (stop line)	41.2	28.6	-30.60%	28.1	-31.81%	16.0	-61.09%
05 (conflict zone)	41.2	27.9	-32.13%	30.0	-27.17%	17.0	-58.80%
06 (stop line)	38.6	31.8	-17.51%	28.8	-25.27%	18.4	-52.30%
06 (conflict zone)	38.9	38.2	-1.82%	30.7	-21.12%	25.1	-35.49%
08 (stop line)	37.0	24.5	-33.63%	23.6	-36.05%	12.9	-65.02%
08 (conflict zone)	37.5	24.1	-35.79%	24.9	-33.70%	13.7	-63.59%
09 (stop line)	41.9	33.0	-21.20%	30.3	-27.77%	18.4	-56.11%
09 (conflict zone)	42.2	47.7	13.00%	31.6	-25.09%	30.4	-27.99%
11 (stop line)	39.7	28.0	-29.52%	28.9	-27.28%	16.5	-58.40%
11 (conflict zone)	39.8	27.4	-31.31%	29.5	-25.92%	18.5	-53.67%
12 (stop line)	39.1	33.8	-13.65%	28.9	-26.19%	19.4	-50.39%
12 (conflict zone)	39.7	39.9	0.67%	30.6	-22.79%	26.3	-33.57%
22	25.1	17.1	-31.97%	10.9	-56.48%	8.1	-67.68%
24	21.8	12.9	-40.77%	5.6	-74.40%	4.4	-79.77%
26	24.4	18.0	-26.54%	11.1	-54.56%	8.3	-66.20%
28	22.3	13.6	-38.89%	5.6	-74.71%	4.5	-79.86%
31	27.9	22.5	-19.33%	13.9	-50.21%	12.3	-55.99%
32	27.8	22.9	-17.61%	12.4	-55.39%	12.4	-55.32%
33	27.3	19.9	-27.07%	7.8	-71.53%	7.3	-73.35%
34	28.1	19.8	-29.40%	7.6	-72.75%	7.6	-72.76%
35	26.9	22.8	-15.12%	13.3	-50.50%	12.1	-55.11%
36	29.4	23.9	-18.81%	13.7	-53.48%	12.2	-58.37%
37	25.8	18.7	-27.78%	7.6	-70.70%	7.5	-71.16%
38	28.4	19.4	-31.76%	7.3	-74.15%	8.2	-71.16%

* Protected conflicts equals 0%.

B.1.3. Major-minor flows south-east

B.1.3.1. Throughput and capacity

The results of the following performance indicators are presented on the following pages:

- Intersection throughput;
- Load ratio;
- Green time;
- Degree of saturation.

Table B-18 | Intersection throughput [pce/h] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [pce/h]	Perm. confl.1: absolute [pce/h]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [pce/h]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [pce/h]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	497.9	496.5	-0.28%	476.3	-4.34%	496.8	-0.22%
02 (conflict zone)	399.3	398.5	-0.20%	381.6	-4.43%	397.8	-0.38%
03 (stop line)	98.6	98.4	-0.20%	95.3	-3.35%	99.1	0.51%
03 (conflict zone)	98.5	98.2	-0.30%	95.0	-3.55%	98.9	0.41%
05 (stop line)	192.3	193.9	0.83%	191.8	-0.26%	194.1	0.94%
05 (conflict zone)	93.8	94.7	0.96%	93.6	-0.21%	95.0	1.28%
06 (stop line)	98.4	98.7	0.30%	98.0	-0.41%	98.8	0.41%
06 (conflict zone)	98.2	98.5	0.31%	98.0	-0.20%	98.7	0.51%
08 (stop line)	191.0	190.8	-0.10%	191.5	0.26%	191.9	0.47%
08 (conflict zone)	92.1	91.9	-0.22%	92.1	0.00%	92.4	0.33%
09 (stop line)	100.9	100.9	0.00%	100.6	-0.30%	100.8	-0.10%
09 (conflict zone)	100.8	100.7	-0.10%	100.3	-0.50%	100.0	-0.79%
11 (stop line)	185.1	186.3	0.65%	185.1	0.00%	186.4	0.70%
11 (conflict zone)	91.2	91.6	0.44%	91.1	-0.11%	91.6	0.44%
12 (stop line)	383.0	386.8	0.99%	384.0	0.26%	387.5	1.17%
12 (conflict zone)	382.7	386.3	0.94%	383.9	0.31%	386.8	1.07%
22	203.9	203.5	-0.20%	203.6	-0.15%	204.3	0.20%
24	196.7	197.3	0.31%	197.6	0.46%	197.6	0.46%
26	201.0	202.6	0.80%	201.7	0.35%	202.7	0.85%
28	205.4	207.8	1.17%	208.1	1.31%	208.1	1.31%
31	99.2	99.3	0.10%	99.2	0.00%	99.7	0.50%
32	98.0	97.4	-0.61%	97.2	-0.82%	97.7	-0.31%
33	100.5	100.5	0.00%	100.9	0.40%	100.8	0.30%
34	93.1	93.4	0.32%	93.4	0.32%	93.4	0.32%
35	96.7	97.8	1.14%	96.9	0.21%	97.5	0.83%
36	97.2	98.6	1.44%	97.6	0.41%	98.3	1.13%
37	94.0	95.1	1.17%	96.0	2.13%	95.6	1.70%
38	98.9	98.9	0.00%	99.7	0.81%	99.7	0.81%

* Protected conflicts equals 0%.

Table B-19 | Load ratio [-] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.204	0.204	-0.28%	0.303	48.41%	0.316	54.60%
02 (conflict zone)	0.164	0.163	-0.20%	0.243	48.26%	0.253	54.36%
03 (stop line)	0.045	0.078	72.07%	0.063	37.58%	0.119	161.28%
03 (conflict zone)	0.045	0.078	71.89%	0.062	37.28%	0.119	161.02%
05 (stop line)	0.086	0.086	0.83%	0.122	42.37%	0.124	44.74%
05 (conflict zone)	0.042	0.042	0.96%	0.060	42.44%	0.061	45.23%
06 (stop line)	0.046	0.077	68.22%	0.064	39.66%	0.115	150.40%
06 (conflict zone)	0.046	0.077	68.22%	0.064	39.94%	0.115	150.66%
08 (stop line)	0.086	0.086	-0.10%	0.121	41.43%	0.122	42.40%
08 (conflict zone)	0.041	0.041	-0.22%	0.058	41.06%	0.059	42.19%
09 (stop line)	0.045	0.081	80.48%	0.067	48.47%	0.122	171.82%
09 (conflict zone)	0.045	0.081	80.30%	0.066	48.17%	0.121	169.93%
11 (stop line)	0.080	0.081	0.65%	0.117	46.82%	0.118	47.75%
11 (conflict zone)	0.039	0.040	0.44%	0.058	46.66%	0.058	47.36%
12 (stop line)	0.155	0.310	99.55%	0.255	64.36%	0.474	205.01%
12 (conflict zone)	0.155	0.309	99.45%	0.255	64.45%	0.473	204.70%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

Table B-20 | Green time [s] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	27.9	22.3	-19.97%	36.6	31.22%	25.6	-8.11%
02 (conflict zone)	27.9	22.3	-19.97%	36.6	31.22%	25.6	-8.11%
03 (stop line)	6.6	7.9	20.95%	14.7	123.95%	8.0	21.17%
03 (conflict zone)	6.6	7.9	20.95%	14.7	123.95%	8.0	21.17%
05 (stop line)	11.0	8.8	-20.09%	11.7	6.29%	8.9	-19.77%
05 (conflict zone)	11.0	8.8	-20.09%	11.7	6.29%	8.9	-19.77%
06 (stop line)	6.0	7.5	25.80%	7.3	22.51%	7.8	30.34%
06 (conflict zone)	6.0	7.5	25.80%	7.3	22.51%	7.8	30.34%
08 (stop line)	10.4	8.6	-17.39%	13.0	24.32%	12.3	17.98%
08 (conflict zone)	10.4	8.6	-17.39%	13.0	24.32%	12.3	17.98%
09 (stop line)	7.6	11.4	50.42%	7.5	-1.65%	11.3	48.54%
09 (conflict zone)	7.6	11.4	50.42%	7.5	-1.65%	11.3	48.54%
11 (stop line)	9.9	8.3	-15.79%	10.0	1.33%	8.7	-12.00%
11 (conflict zone)	9.9	8.3	-15.79%	10.0	1.33%	8.7	-12.00%
12 (stop line)	20.3	23.8	17.18%	25.3	24.26%	24.7	21.35%
12 (conflict zone)	20.3	23.8	17.18%	25.3	24.26%	24.7	21.35%
22	10.4	12.2	17.41%	46.9	351.16%	30.5	193.65%
24	16.5	20.4	23.55%	42.7	158.78%	35.4	114.17%
26	16.4	23.9	45.75%	44.8	172.84%	28.9	76.22%
28	17.9	17.6	-1.28%	50.8	184.15%	31.6	76.87%
31	8.9	9.3	4.58%	8.3	-6.09%	8.5	-3.51%
32	8.6	8.9	3.53%	8.7	0.35%	8.7	0.37%
33	8.6	8.5	-0.67%	8.2	-4.17%	8.2	-3.69%
34	7.9	7.8	-1.32%	8.1	2.38%	8.1	2.65%
35	9.3	8.8	-5.31%	8.7	-6.21%	8.6	-7.61%
36	8.6	8.2	-4.65%	8.6	-0.86%	8.5	-1.42%
37	9.6	9.4	-1.98%	8.4	-12.38%	8.6	-10.53%
38	9.7	9.2	-5.43%	8.6	-11.87%	8.6	-11.08%

* Protected conflicts equals 0%.

Table B-21 | Degree of saturation [-] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [-]	Perm. confl.1: absolute [-]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [-]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [-]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.801	0.751	-6.27%	0.853	6.47%	0.846	5.58%
02 (conflict zone)	0.643	0.603	-6.20%	0.683	6.37%	0.677	5.42%
03 (stop line)	0.782	0.964	23.26%	0.487	-37.71%	1.114	42.51%
03 (conflict zone)	0.781	0.962	23.13%	0.485	-37.84%	1.112	42.37%
05 (stop line)	0.874	0.807	-7.65%	1.095	25.25%	0.939	7.51%
05 (conflict zone)	0.426	0.394	-7.53%	0.534	25.31%	0.460	7.87%
06 (stop line)	0.722	0.981	35.92%	0.916	26.90%	1.257	74.17%
06 (conflict zone)	0.720	0.979	35.92%	0.916	27.16%	1.256	74.35%
08 (stop line)	0.863	0.733	-15.09%	0.750	-13.11%	0.499	-42.16%
08 (conflict zone)	0.416	0.353	-15.19%	0.361	-13.33%	0.240	-42.24%
09 (stop line)	0.721	0.706	-2.02%	1.051	45.81%	0.950	31.74%
09 (conflict zone)	0.720	0.705	-2.11%	1.048	45.52%	0.942	30.82%
11 (stop line)	0.832	0.789	-5.19%	0.963	15.78%	0.811	-2.53%
11 (conflict zone)	0.410	0.388	-5.38%	0.474	15.66%	0.398	-2.78%
12 (stop line)	0.824	1.091	32.40%	1.036	25.75%	1.336	62.11%
12 (conflict zone)	0.823	1.090	32.34%	1.036	25.81%	1.333	61.94%
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Protected conflicts equals 0%.

B.1.3.2. Queues

The results of the following performance indicators are presented on the following pages:

- Queue length;
- Number of stops.

Table B-22 | Queue length [m] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [m]	Perm. confl.1: absolute [m]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [m]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [m]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	47.7	29.3	-38.56%	100.8	111.14%	31.1	-34.75%
02 (conflict zone)	47.8	29.4	-38.52%	102.5	114.71%	32.8	-31.40%
03 (stop line)	8.7	6.6	-24.96%	6.8	-21.55%	3.3	-62.17%
03 (conflict zone)	8.7	8.1	-7.48%	7.1	-18.42%	5.0	-42.30%
05 (stop line)	16.4	11.8	-28.32%	15.9	-3.55%	10.1	-38.82%
05 (conflict zone)	16.5	11.8	-28.24%	16.1	-2.30%	10.4	-36.64%
06 (stop line)	5.2	7.2	40.04%	7.0	35.87%	5.0	-3.34%
06 (conflict zone)	5.2	8.8	70.71%	7.4	42.72%	7.3	41.65%
08 (stop line)	15.6	10.5	-32.53%	10.3	-33.88%	5.2	-66.76%
08 (conflict zone)	15.6	10.6	-32.45%	10.5	-32.56%	5.4	-65.68%
09 (stop line)	8.4	9.0	7.46%	9.0	7.76%	9.1	8.56%
09 (conflict zone)	8.4	13.9	65.78%	9.3	11.32%	16.2	92.68%
11 (stop line)	14.6	11.1	-23.88%	11.5	-20.92%	7.9	-45.73%
11 (conflict zone)	14.6	11.1	-23.80%	11.9	-18.41%	8.3	-43.26%
12 (stop line)	36.1	24.8	-31.35%	33.4	-7.43%	24.1	-33.34%
12 (conflict zone)	36.1	27.1	-24.92%	34.4	-4.72%	28.4	-21.34%
22	2.3	2.6	12.47%	1.3	-44.80%	1.3	-46.37%
24	1.4	1.0	-28.93%	0.7	-49.53%	0.6	-55.84%
26	2.9	2.0	-29.81%	1.7	-41.16%	1.3	-54.03%
28	3.3	2.5	-23.61%	1.4	-57.48%	1.2	-64.96%
31	3.0	3.1	3.84%	2.8	-5.95%	2.8	-5.61%
32	2.8	2.9	3.38%	2.6	-8.41%	2.6	-6.69%
33	2.7	2.6	-1.84%	2.5	-6.16%	2.5	-4.30%
34	2.6	2.6	-1.43%	2.4	-6.77%	2.5	-6.14%
35	3.0	2.9	-5.30%	2.8	-7.51%	2.8	-8.66%
36	3.1	2.9	-6.03%	2.8	-8.95%	2.8	-10.38%
37	3.0	2.8	-4.70%	2.5	-14.95%	2.5	-15.09%
38	3.3	3.2	-4.21%	2.8	-14.57%	2.8	-13.72%

* Protected conflicts equals 0%.

Table B-23 | Stops [#] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [#]	Perm. confl.1: absolute [#]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [#]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [#]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	0.961	0.854	-11.11%	2.354	145.10%	1.206	25.54%
02 (conflict zone)	0.962	0.856	-10.95%	2.648	175.41%	1.455	51.33%
03 (stop line)	1.071	1.052	-1.75%	1.661	55.05%	0.908	-15.19%
03 (conflict zone)	1.072	1.624	51.54%	1.771	65.24%	1.563	45.85%
05 (stop line)	0.929	0.876	-5.75%	0.946	1.81%	0.874	-5.96%
05 (conflict zone)	0.933	0.873	-6.44%	1.103	18.29%	1.123	20.37%
06 (stop line)	0.817	1.054	28.99%	0.927	13.49%	0.910	11.39%
06 (conflict zone)	0.819	1.645	100.91%	1.059	29.38%	1.785	118.09%
08 (stop line)	0.925	0.860	-6.99%	0.795	-14.11%	0.633	-31.59%
08 (conflict zone)	0.924	0.867	-6.13%	0.977	5.72%	0.751	-18.67%
09 (stop line)	0.928	1.241	33.79%	0.967	4.26%	1.367	47.39%
09 (conflict zone)	0.927	2.184	135.74%	1.086	17.19%	3.307	256.94%
11 (stop line)	0.991	0.897	-9.56%	0.982	-0.91%	0.887	-10.52%
11 (conflict zone)	1.002	0.905	-9.66%	1.298	29.52%	1.157	15.44%
12 (stop line)	0.946	1.167	23.45%	1.065	12.64%	1.318	39.36%
12 (conflict zone)	0.946	1.387	46.60%	1.157	22.28%	1.741	83.95%
22	0.906	0.944	4.22%	0.521	-42.48%	0.547	-39.58%
24	0.637	0.518	-18.75%	0.368	-42.20%	0.376	-41.06%
26	0.988	0.778	-21.22%	0.634	-35.88%	0.586	-40.72%
28	1.044	0.887	-15.10%	0.548	-47.51%	0.543	-48.02%
31	0.824	0.854	3.65%	0.640	-22.29%	0.682	-17.29%
32	0.858	0.868	1.21%	0.681	-20.67%	0.764	-10.99%
33	0.687	0.672	-2.26%	0.479	-30.27%	0.563	-18.07%
34	0.772	0.728	-5.68%	0.555	-28.02%	0.622	-19.40%
35	0.863	0.784	-9.11%	0.658	-23.76%	0.716	-17.08%
36	0.872	0.822	-5.78%	0.729	-16.36%	0.740	-15.17%
37	0.895	0.842	-5.89%	0.623	-30.42%	0.679	-24.09%
38	0.916	0.883	-3.52%	0.640	-30.07%	0.699	-23.65%

* Protected conflicts equals 0%.

B.1.3.3. Travel times and delays

The results of the following performance indicators are presented on the following pages:

- Cycle time;
- Delays.

Table B-24 | Cycle time [s] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [s]	Perm. confl.1: absolute [s]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	109.4	82.3	-24.78%	103.0	-5.86%	68.7	-37.24%
02 (conflict zone)	109.4	82.3	-24.78%	103.0	-5.86%	68.7	-37.24%
03 (stop line)	112.8	97.7	-13.36%	114.4	1.40%	74.5	-33.91%
03 (conflict zone)	112.8	97.7	-13.36%	114.4	1.40%	74.5	-33.91%
05 (stop line)	112.5	82.3	-26.81%	105.2	-6.50%	67.0	-40.41%
05 (conflict zone)	112.5	82.3	-26.81%	105.2	-6.50%	67.0	-40.41%
06 (stop line)	94.0	95.5	1.64%	104.6	11.32%	85.2	-9.34%
06 (conflict zone)	94.0	95.5	1.64%	104.6	11.32%	85.2	-9.34%
08 (stop line)	105.3	73.9	-29.78%	80.4	-23.62%	50.5	-52.08%
08 (conflict zone)	105.3	73.9	-29.78%	80.4	-23.62%	50.5	-52.08%
09 (stop line)	122.0	99.6	-18.34%	117.9	-3.40%	87.8	-28.01%
09 (conflict zone)	122.0	99.6	-18.34%	117.9	-3.40%	87.8	-28.01%
11 (stop line)	102.4	81.3	-20.68%	81.9	-20.09%	59.5	-41.95%
11 (conflict zone)	102.4	81.3	-20.68%	81.9	-20.09%	59.5	-41.95%
12 (stop line)	108.0	84.0	-22.25%	102.7	-4.94%	69.6	-35.50%
12 (conflict zone)	108.0	84.0	-22.25%	102.7	-4.94%	69.6	-35.50%
22	62.3	76.5	22.68%	92.0	47.59%	67.8	8.82%
24	49.6	48.8	-1.48%	70.0	41.23%	59.0	19.01%
26	87.3	77.1	-11.67%	101.7	16.53%	68.9	-21.05%
28	109.3	82.2	-24.81%	101.1	-7.50%	68.0	-37.73%
31	64.9	81.3	25.33%	44.5	-31.36%	48.6	-25.01%
32	67.7	82.5	21.79%	45.5	-32.79%	47.9	-29.27%
33	46.5	43.2	-7.08%	37.0	-20.50%	38.4	-17.40%
34	45.7	43.5	-4.64%	36.7	-19.56%	37.9	-17.12%
35	82.7	62.1	-24.93%	51.2	-38.09%	49.1	-40.62%
36	80.9	62.6	-22.70%	50.6	-37.44%	50.7	-37.41%
37	105.6	80.9	-23.45%	44.2	-58.19%	47.2	-55.30%
38	110.7	82.5	-25.51%	44.7	-59.63%	47.1	-57.47%

* Protected conflicts equals 0%.

Table B-25 | Delay [s/pce] per signal group, for major-minor flows south-east.

Signal group	Prot. confl.: absolute [s/pce]	Perm. confl.1: absolute [s/pce]	Perm. confl.1: relative [%]*	Perm. confl.2: absolute [s/pce]	Perm. confl.2: relative [%]*	Perm. confl.1 & 2: absolute [s/pce]	Perm. confl.1 & 2: relative [%]*
02 (stop line)	47.7	32.1	-32.61%	92.2	93.44%	32.8	-31.12%
02 (conflict zone)	47.5	31.8	-33.06%	94.2	98.21%	34.7	-27.06%
03 (stop line)	59.0	41.8	-29.09%	76.8	30.25%	24.9	-57.86%
03 (conflict zone)	59.2	48.8	-17.59%	78.8	32.98%	32.3	-45.52%
05 (stop line)	49.7	37.0	-25.67%	47.9	-3.65%	31.6	-36.51%
05 (conflict zone)	51.4	36.7	-28.48%	49.0	-4.57%	32.6	-36.55%
06 (stop line)	33.6	45.2	34.66%	44.3	31.96%	31.0	-7.56%
06 (conflict zone)	34.0	52.6	54.52%	46.5	36.69%	40.5	19.01%
08 (stop line)	48.5	33.4	-31.05%	32.7	-32.64%	17.7	-63.41%
08 (conflict zone)	48.3	33.7	-30.26%	34.2	-29.21%	18.0	-62.66%
09 (stop line)	50.4	49.9	-1.12%	53.2	5.40%	49.9	-1.14%
09 (conflict zone)	50.5	68.6	35.78%	55.1	9.05%	74.6	47.64%
11 (stop line)	48.4	37.6	-22.25%	38.9	-19.59%	27.9	-42.28%
11 (conflict zone)	48.7	37.6	-22.90%	41.2	-15.39%	29.5	-39.34%
12 (stop line)	47.9	35.3	-26.18%	45.5	-4.89%	33.1	-30.84%
12 (conflict zone)	48.0	38.1	-20.62%	47.3	-1.47%	38.3	-20.06%
22	22.2	26.7	19.91%	11.2	-49.79%	10.7	-51.74%
24	11.8	7.8	-33.63%	5.6	-52.30%	4.9	-58.79%
26	32.0	19.5	-39.22%	15.8	-50.68%	11.4	-64.43%
28	37.5	24.9	-33.45%	12.9	-65.58%	9.7	-74.05%
31	23.6	31.9	35.17%	14.9	-36.65%	16.1	-31.81%
32	25.0	31.4	25.61%	14.4	-42.53%	15.9	-36.34%
33	13.5	11.6	-14.23%	6.9	-48.68%	8.9	-33.84%
34	16.0	13.2	-17.25%	7.8	-51.35%	8.8	-44.80%
35	34.5	23.1	-33.00%	20.1	-41.55%	16.3	-52.58%
36	36.6	23.7	-35.33%	19.5	-46.73%	16.5	-55.00%
37	46.0	32.3	-29.61%	15.7	-65.80%	14.6	-68.33%
38	45.4	33.0	-27.19%	15.3	-66.22%	14.6	-67.90%

* Protected conflicts equals 0%.

B.2. Results per mode

The results per mode are the averaged results of signal groups:

- *Car*: signal groups 02, 03, 05, 06, 08, 09, 11, and 12;
- *Bicycle*: signal groups 22, 24, 26, and 28;
- *Pedestrian*: signal groups 31, 32, 33, 34, 35, 36, 37, and 38;
- *Total*: all signal groups.

For car signal groups, a further distinction is made between the stop line, and conflict zone.

B.2.1. Throughput and capacity

The results of the following performance indicators are presented on the following pages:

- Intersection throughput;
- Load ratio;
- Green time;
- Degree of saturation.

Table B-26 | Intersection throughput [pce/h] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [pce/h]	Car (conflict zone) [pce/h]	Bicycle [#/h]	Pedestrian [#/h]	Total [#/h]
Prot. confl. (EF*)	290.9	193.5	201.2	96.7	195.3
Prot. confl. (MM NS*)	220.2	96.1	202.1	97.2	167.4
Prot. confl. (MM SE*)	218.4	169.6	201.8	97.2	166.6
Perm. confl. 1 (EF*)	292.7	194.0	201.7	96.8	196.1
Perm. confl. 1 (MM NS*)	220.7	96.4	202.6	97.4	167.8
Perm. confl. 1 (MM SE*)	219.0	170.1	202.8	97.6	167.2
Perm. confl. 2 (EF*)	290.0	192.9	202.3	97.5	195.4
Perm. confl. 2 (MM NS*)	221.3	96.4	203.0	97.8	168.2
Perm. confl. 2 (MM SE*)	215.3	167.0	202.8	97.6	165.7
Perm. confl. 1 & 2 (EF*)	293.5	194.5	203.1	97.8	197.1
Perm. confl. 1 & 2 (MM NS*)	221.5	96.6	203.1	98.0	168.4
Perm. confl. 1 & 2 (MM SE*)	219.4	170.2	203.2	97.8	167.5

* EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

Table B-27 | Load ratio [-] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [-]	Car (conflict zone) [-]	Bicycle [-]	Pedestrian [-]	Total [-]
Prot. confl. (EF*)	0.127	0.085	N/A	N/A	N/A
Prot. confl. (MM NS*)	0.096	0.042	N/A	N/A	N/A
Prot. confl. (MM SE*)	0.093	0.072	N/A	N/A	N/A
Perm. confl. 1 (EF*)	0.162	0.119	N/A	N/A	N/A
Perm. confl. 1 (MM NS*)	0.113	0.060	N/A	N/A	N/A
Perm. confl. 1 (MM SE*)	0.125	0.104	N/A	N/A	N/A
Perm. confl. 2 (EF*)	0.186	0.125	N/A	N/A	N/A
Perm. confl. 2 (MM NS*)	0.142	0.062	N/A	N/A	N/A
Perm. confl. 2 (MM SE*)	0.139	0.108	N/A	N/A	N/A
Perm. confl. 1 & 2 (EF*)	0.242	0.178	N/A	N/A	N/A
Perm. confl. 1 & 2 (MM NS*)	0.169	0.089	N/A	N/A	N/A
Perm. confl. 1 & 2 (MM SE*)	0.189	0.157	N/A	N/A	N/A

Table B-28 | Green time [s] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [s]	Car (conflict zone) [s]	Bicycle [s]	Pedestrian [s]	Total [s]
Prot. confl. (EF*)	17.7	17.7	14.3	9.2	13.7
Prot. confl. (MM NS*)	10.7	10.7	13.9	8.9	10.6
Prot. confl. (MM SE*)	12.5	12.5	15.3	8.9	11.6
Perm. confl. 1 (EF*)	20.9	20.9	19.0	9.1	15.8
Perm. confl. 1 (MM NS*)	9.2	9.2	14.7	8.6	10.0
Perm. confl. 1 (MM SE*)	12.3	12.3	18.5	8.8	12.2
Perm. confl. 2 (EF*)	22.0	22.0	54.5	8.5	23.1
Perm. confl. 2 (MM NS*)	9.3	9.3	30.5	8.4	13.2
Perm. confl. 2 (MM SE*)	15.8	15.8	46.3	8.4	18.9
Perm. confl. 1 & 2 (EF*)	18.1	18.1	36.2	8.5	17.9
Perm. confl. 1 & 2 (MM NS*)	7.6	7.6	18.3	8.3	10.0
Perm. confl. 1 & 2 (MM SE*)	13.4	13.4	31.6	8.5	15.1

* EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

Table B-29 | Degree of saturation [-] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [-]	Car (conflict zone) [-]	Bicycle [-]	Pedestrian [-]	Total [-]
Prot. confl. (EF*)	0.864	0.648	N/A	N/A	N/A
Prot. confl. (MM NS*)	0.732	0.453	N/A	N/A	N/A
Prot. confl. (MM SE*)	0.802	0.617	N/A	N/A	N/A
Perm. confl. 1 (EF*)	0.766	0.553	N/A	N/A	N/A
Perm. confl. 1 (MM NS*)	0.885	0.617	N/A	N/A	N/A
Perm. confl. 1 (MM SE*)	0.853	0.684	N/A	N/A	N/A
Perm. confl. 2 (EF*)	1.021	0.764	N/A	N/A	N/A
Perm. confl. 2 (MM NS*)	0.989	0.626	N/A	N/A	N/A
Perm. confl. 2 (MM SE*)	0.894	0.692	N/A	N/A	N/A
Perm. confl. 1 & 2 (EF*)	0.962	0.718	N/A	N/A	N/A
Perm. confl. 1 & 2 (MM NS*)	1.142	0.833	N/A	N/A	N/A
Perm. confl. 1 & 2 (MM SE*)	0.969	0.802	N/A	N/A	N/A

B.2.2. Queues

The results of the following performance indicators are presented on the following pages:

- Queue length;
- Number of stops.

Table B-30 | Queue length [m] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [m]	Car (conflict zone) [m]	Bicycle [m]	Pedestrian [m]	Total [m]
Prot. confl. (EF*)	32.8	65.6	3.1	3.1	15.0
Prot. confl. (MM NS*)	14.9	29.7	2.4	2.9	7.6
Prot. confl. (MM SE*)	19.1	38.2	2.5	2.9	9.3
Perm. confl. 1 (EF*)	25.1	52.7	2.6	3.0	11.8
Perm. confl. 1 (MM NS*)	9.4	19.1	1.0	2.6	5.0
Perm. confl. 1 (MM SE*)	13.8	28.9	2.0	2.9	7.1
Perm. confl. 2 (EF*)	40.1	80.9	1.6	2.7	17.5
Perm. confl. 2 (MM NS*)	8.9	18.1	1.0	2.6	4.8
Perm. confl. 2 (MM SE*)	24.4	49.3	1.3	2.7	11.1
Perm. confl. 1 & 2 (EF*)	18.4	40.5	1.2	2.7	8.7
Perm. confl. 1 & 2 (MM NS*)	4.9	11.1	0.8	2.6	3.1
Perm. confl. 1 & 2 (MM SE*)	12.0	26.2	1.1	2.7	6.1

* EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

Table B-31 | Number of stops [#] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [#]	Car (conflict zone) [#]	Bicycle [#]	Pedestrian [#]	Total [#]
Prot. confl. (EF*)	1.023	1.024	1.032	0.878	0.967
Prot. confl. (MM NS*)	0.913	0.912	0.882	0.839	0.877
Prot. confl. (MM SE*)	0.946	0.948	0.894	0.836	0.891
Perm. confl. 1 (EF*)	1.213	1.490	0.911	0.871	1.016
Perm. confl. 1 (MM NS*)	0.904	1.261	0.748	0.825	0.841
Perm. confl. 1 (MM SE*)	1.000	1.293	0.782	0.807	0.879
Perm. confl. 2 (EF*)	1.239	1.394	0.578	0.643	0.868
Perm. confl. 2 (MM NS*)	0.855	0.969	0.494	0.640	0.697
Perm. confl. 2 (MM SE*)	1.212	1.387	0.518	0.626	0.839
Perm. confl. 1 & 2 (EF*)	1.202	1.771	0.509	0.687	0.858
Perm. confl. 1 & 2 (MM NS*)	0.746	1.233	0.488	0.670	0.664
Perm. confl. 1 & 2 (MM SE*)	1.013	1.610	0.513	0.683	0.781

B.2.3. Travel times and delays

The results of the following performance indicators are presented on the following pages:

- Cycle time;
- Delays.

Table B-32 | Cycle time [s] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [s]	Car (conflict zone) [s]	Bicycle [s]	Pedestrian [s]	Total [s]
Prot. confl. (EF*)	119.7	119.7	92.7	92.5	103.4
Prot. confl. (MM NS*)	90.2	90.2	66.4	66.3	75.9
Prot. confl. (MM SE*)	108.3	108.3	77.1	75.6	89.0
Perm. confl. 1 (EF*)	98.2	98.2	89.0	82.9	90.2
Perm. confl. 1 (MM NS*)	73.7	73.7	57.1	60.1	64.9
Perm. confl. 1 (MM SE*)	87.1	87.1	71.1	67.3	76.0
Perm. confl. 2 (EF*)	122.7	122.7	110.7	47.4	90.2
Perm. confl. 2 (MM NS*)	75.4	75.4	62.6	41.0	59.1
Perm. confl. 2 (MM SE*)	101.2	101.2	91.2	44.3	76.5
Perm. confl. 1 & 2 (EF*)	72.4	72.4	75.5	47.4	63.0
Perm. confl. 1 & 2 (MM NS*)	54.8	54.8	41.9	41.6	46.9
Perm. confl. 1 & 2 (MM SE*)	70.4	70.4	66.0	45.9	59.7

* EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

Table B-33 | Delay [s/pce] averaged per mode.

Conflict type (traffic flow volume scenario)	Car (stop line) [s/pce]	Car (conflict zone) [s/pce]	Bicycle [s/pce]	Pedestrian [s/pce]	Total [s/pce]
Prot. confl. (EF*)	58.1	57.9	35.6	40.3	46.5
Prot. confl. (MM NS*)	39.6	39.8	23.4	27.7	31.6
Prot. confl. (MM SE*)	48.1	48.4	25.9	30.1	36.5
Perm. confl. 1 (EF*)	50.0	55.0	27.7	34.6	39.4
Perm. confl. 1 (MM NS*)	29.5	34.7	15.4	21.2	23.4
Perm. confl. 1 (MM SE*)	39.0	43.5	19.7	25.0	29.6
Perm. confl. 2 (EF*)	68.3	69.8	15.8	18.0	37.7
Perm. confl. 2 (MM NS*)	27.5	28.9	8.3	10.5	16.9
Perm. confl. 2 (MM SE*)	53.9	55.8	11.4	14.3	29.6
Perm. confl. 1 & 2 (EF*)	38.7	46.3	10.1	15.6	23.7
Perm. confl. 1 & 2 (MM NS*)	16.6	21.9	6.3	9.9	11.9
Perm. confl. 1 & 2 (MM SE*)	31.1	37.6	9.2	14.0	19.9

* EF = equal flows (scenario 1); MM NS = major-minor flows north-south (scenario 2); MM SE = major-minor flows south-east (scenario 3).

C. Clearance times

The clearance times are computed for all conflicts. That way, the resulting clearance time matrix represents the matrix for a conflict-free traffic signal controller, thus protected conflicts only. The clearance times are computed using the formulas provided by the Dutch guidelines (CROW, 2013):

$$t_{\text{exit}} = \frac{L_{\text{exit}} + l_{\text{exit}}}{v_{\text{exit}}} \tag{C-1}$$

$$t_{\text{enter}} = t_r + \sqrt{\frac{2L_{\text{enter}}}{a_{\text{acc}} + a_{\text{dec}}}} \tag{C-2}$$

$$t_{\text{clear},i,j} = t_{\text{exit},i} - t_{\text{enter},j} \mid t_{\text{clear},i,j} \geq 0 \tag{C-3}$$

In these formulas, the clearance time t_{clear} [s] is computed as the difference in the time t_{exit} [s] needed for signal group i to clear the conflict zone, and the time t_{enter} [s] needed for conflicting signal group j to reach the conflict zone. The Dutch guidelines explicitly state that the clearance time might not be negative, hence the condition $t_{\text{clear}} \geq 0$ s (although this condition is about to be removed from the Dutch guidelines, the condition is still used in this research, for simplicity). Furthermore, t_{exit} [s], and t_{enter} [s] are separately computed, whereas the former depends on the distance L_{exit} [m] from the stop line to where the conflict zone is completely cleared, the vehicle length l_{exit} [m] of vehicle exiting conflict zone, and the speed v_{exit} [m/s] of a vehicle clearing the conflict zone. In general, the values $l_{\text{exit}} = 6$ m for passenger cars, and $v_{\text{exit}} = 12$ m/s are applied. The entrance time t_{enter} includes the distance L_{enter} [m] from the stop line to the conflict zone, and the acceleration rate a_{acc} [m/s²], and deceleration rate a_{dec} [m/s²] of vehicles at the stop line. Also, the reaction time t_r [s] is included explicitly. Then, fixed values are used for the latter three variables, namely $a_{\text{acc}} = a_{\text{dec}} = 2.5$ m/s², and $t_r = 1$ s.

Moreover, the clearance times are computed using a specialist computer program OTTO in which the paths of signal groups on an intersection are drawn, after which the program computes the clearance times automatically using the formulas listed above. Then, the resulting clearance time matrix for all conflicts is given in Table C-1, whereas the underlined clearance timers correspond to conflicts that might be controlled as permitted conflicts, and should therefore be removed from the matrix if permissive phasing is applied.

Table C-1 | Clearance times for the synthetic intersection. Clearance times that are underlined correspond to conflicts that are considered as permitted conflicts, and consequently might be removed from the clearance times matrix.

	02	03	05	06	08	09	11	12	22	24	26	28	31	32	33	34	35	36	37	38
02	×		0.1	0.0		0.0	0.4	0.0	0.4		2.9	3.6	1.9					3.3		5.1
03		×	1.2	2.3	3.2		1.9	0.9	1.2	6.3			1.9			7.1				
05	0.3	0.0	×		0.0	0.0		0.0	3.5	0.3		2.8		4.1	1.9					3.2
06	1.8	0.9		×	1.1	2.1	3.2			1.1	6.3				0.2			7.1		
08		0.0	0.4	0.0	×		0.1	0.0	2.8	3.5	0.4			3.4		5.1	1.9			
09	3.3		1.9	1.0		×	1.2	2.2			1.2	6.4					1.9			7.1
11	0.0	0.0		0.0	0.3	0.0	×			2.8	3.6	0.3				3.3		5.0	1.9	
12	1.1	2.1	3.2		1.7	0.8		×	6.2			1.1		7.1					1.9	
22	2.3	1.4	0.0		0.0			0.0	×											
24		0.0	2.3	1.5	0.0		0.0			×										
26	0.0			0.0	2.2	1.4	0.0				×									
28	0.0		0.0			0.0	2.4	1.5				×								
31	5.0	5.0											×							
32			0.2		0.0			0.0						×						
33			5.1	5.2											×					
34		0.0			0.4		0.0									×				
35					5.0	5.1											×			
36	0.0			0.0			0.4											×		
37							5.1	5.2											×	
38	0.4		0.0			0.0														×