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ÚSTAV POČÍTAČOVÉ GRAFIKY A MULTIMÉDIÍ

MANAGEMENT OF TRAFFIC LIGHTS

BACHELOR’S THESIS
BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis Specification

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Student: **Piaček Adrián**
Programme: Information Technology
Title: **Management of Traffic Lights**
Category: Modelling and Simulation

Assignment:

1. Summarize key terms and concepts related to managing the road traffic using traffic lights. Propose your own, or find an existing, abstraction of the management system and its environment.
2. Choose a traffic node and means for modeling traffic systems (roads, vehicles, pedestrians etc.) and analyzing their properties (e.g., the traffic throughput).
3. Use the means from the step 2 to create a model of a system of traffic lights. At least, the model must involve participants of the traffic and allow monitoring of key traffic events and their impact on the traffic.
4. Demonstrate the applicability of your model in various traffic scenarios.
5. Critically evaluate your model and suggest its extension/modification.

Recommended literature:

- According to the supervisor's recommendation.

Requirements for the first semester:

- Complete items 1 and 2 of the assignment, create a basic model able to control the road traffic based on traffic lights.

Detailed formal requirements can be found at https://www.fit.vut.cz/study/theses/

Supervisor: **Strnadel Josef, Ing., Ph.D.**
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Abstract

This paper is centered around the management of traffic lights, thus main element that is targeted throughout whole thesis is traffic control specifically via traffic lights. Furthermore, paper focuses on timings of traffic lights to ensure traffic fluency and afterwards on an analysis of the efficiency of updated traffic signal management plans. Various approaches to the traffic control are researched and implemented in order to establish differences to be later on compared.

Abstrakt

Bakalárka práca sa zaoberá správou križovatkovej signalizácie. Hlavným prvkom signalizácie využívanej vrámci práce sú križovatkové svetlá.

Teoretická časť obsahuje prehľad terminológie pre zabezpečenie unimorfného porozumenia problematiky. Prvá časť sa zaoberá definovaním a vysvetlením konceptu modelovania a simulácie, a s týmito odvetviami spojenými termínmi. Druhá časť obsahuje vysvetlenie problematiky dopravy. Dopravná problematika sa zaoberá špecifikáciou užívateľov dopravy, bezpečenosťou premávky, dopravnými nehodami, a následne aj hlavným zameraním na koncept križovatkových svetiel.

V podkapitole zaoberajúcej sa dopravnými nehodami sa taktiež vyskytujú viaceré revolučné spôsoby minimalizácie vplyvu dopravných nehôd formou úpravy transportačnej infraštruktúry. Podkapitola križovatkových svetiel je zameraná na definíciu prínosu a implementácie týchto zariadení. Princíp spravovania križovatkových fáz je vysvetlený na typickej štvorsmernej križovatke za pomoci ring-and-barrier diagramu. Táto podkapitola taktiež obsahuje definíciu plánu riadenia svetlenej signalizácie križovatiek, ktorý je elementárnou súčasťou vytvárania vylepšených a optimalizovaných riešení v tejto bakalárskej práci. Za poslednú podkapitolu dopravnej problematiky bola zvolená problematika odbočovania vľavo. Doležitosť tejto podkapitoly zdôrazňuje fakt, že ide o najnebezpečnejší šoférovací manéver spojený s dopravnými križovatkami. Podkapitola úvadza dva rozdielne prístupy k problému. Jeden zo smeru bezpečnosti, a to presnejšie chránené odbočovanie vľavo. To je vykonávané pomocou dodatočnej fázy určenej len pre toto odbočovanie, ktoré má však ako dôsledok aj zníženie priepustnosti križovatky. Druhý skúmaný prístup k odbočovaniu vľavo je viac zameraný na efektivitu križovatky, avšak zároveň je náchylnejší na dopravné nehody. Neochránené odbočovanie vľavo ale vychádza z predpokladu, že oproti idúce dopravné prúdy umožňujú odbočovanie vľavo formou medzier v plynulosti premávky.

V teoretickej časti práce je taktiež uvedený prehľad simulačných softvérových možností, ktoré môžu byť použité pri vytváraní a následnom experimentovaní so zvoleným problémom. Väčší dôraz je následne kladený na simulačný softvér použitý pri realizácii výskumnej časti bakalárskej práce. Táto podkapitola obsahuje prehľad základných prostriedkov zvoleného simulačného softvéru, ktoré boli použité pri vytváraní modelu, ako aj pri samotnej optimalizácii plánov riadenia svetlenej signalizácie križovatiek. Taktiež je vysvetlený spôsob zhromažďovania meraných cieľov práce pomocou zvoleného simulačného softvéru.

V časti vytvárania modelu bol zvolený dopravný úsek reprezentujúci časť mestskej dopravnej siete často sa vyskytujúci v blízkosti centra mesta. To znamená, že väčšina zamestnanej populácie v rozvinutých krajinách príde do kontaktu s týmto typom križovatky na každodennej báze. Samotný zvolený dopravný uzol je formou generalizácie,

nakoľko neodpovedá konkrétnemu dopravnému úseku. Pre stanovenie zvládnuteľnej mierky problému bola zvolená časť dopravnej siete obsahujúca mierne neštandardnú štvorsmerú križovatku, priamo napojenú na typickú križovatku s tvarom T. Zvolený dopravný uzol odpovedá 19 dopravným cestám a 12 peším. Cesty určené len pre motorizovanú dopravu odpovedajú viac než 3 kilometrom použiteľných dopravných ciest.

Vytvorený model má špecifikované predvolené konfigurácie vytvorené formou zvoleného simulačného softvéru. Tie sú následne považované za základné konfiguračné nastavenia svetelnej signalizácie a všetky sukcesívne vylepšenia sú voči nim porovnávané. Ťažiskom všetkých vylepšení sú fázy križovatkových svetiel. Možnosti ich konfigurácie a všetky limitácie týchto prístupov a ich preferované použitie v rozlišných dopravných situáciách sú kriticky analyzované.

V neposlednom rade je v časti vytvárania modelu definované rozdelenie a špecifikácia použitých dopravných aktérov. Toto rozdelenie bolo určené na základe informácií získaných od Európskeho Štatistického Úradu (EUROSTAT). Model obsahuje 4 typy bežných dopravných vozidiel, každé z nich s inými fyzikálnymi vlastnosťami.

Simulačný model zvolenej časti dopravnej siete obsahuje taktiež verejnú dopravu. Systém správy verejnej dopravy je z veľkej časti prispôsobený verejnej doprave v meste Brno, avšak nie je mu úplne izomorfný.

V poslednom rade je doležité taktiež spomenúť spôsob rozdelenia simulácie na viaceré časové intervaly. V priebehu simulácie je model prispôsobený jednému dňu, počas ktorého obsahuje 5 časových intervalov simulujúcich predpokladaný dopravný nápor na zvolený dopravný uzol. Každý časový interval obsahuje diametrálne odlišné dopravné vyťaženie na zvolenom dopravnom uzle. Zámer za voľbou viacerých časových úsekov bolo adekvátne simulovanie dopravných špičiek a ich vplyv na zvolenie optimálnej konfigurácie križovatkových svetiel. Skúmaný je taktiež nárast dopravného zaťaženia v nasledujúcich časových intervaloch spôsobený dopravnou vyťaženosťou ciest počas dopravných špičiek. Nakoľko je model reprezentáciou časti dopravnej siete v blízkosti centra mesta, tak aj samotná doprava je rovnako zameraná. Fiktívne centrum mesta bolo určené na juhozápade modelu. Vrámci prvej dopravnej špičky je doprava smerovaná hlavne na juhozápad a vrámci druhej presne opačným spôsobom. Zvolená orientácia dopravy je použitá pre simuláciu každodennej mobility zamestnanej populácie.

V experimentálnej časti je kladený dôraz na časové konfigurovanie križovatkových svetiel pre zabezpečenie premávkovej plynulosti. Následná analýza efektívnosti konfigurácie plánu riadenia svetlenej signalizácie križovatiek určuje správnosť predošlej zvolenej zmeny v konfigurácii a možnosť jej následnej expanzie. Rôznorodé dynamické, ako aj statické prístupy ku správe premávky na križovatkách sú preskúmané a implementované pre definíciu ich rozdielov a ich následné porovnávanie. Pri statickom nastavení plánov riadenia svetlenej signalizácie križovatiek sa experimentuje s nemennými dĺžkami jednotlivých fáz počas celej doby simulácie, ako aj s premenlivými dĺžkami pre jednotlivé fázy a ich časové intervaly. Tento prístup má za cieľ adekvátne preskúmanie možností optimalizácie statických svetelných križovatiek bez nutnosti reštrukturalizácie dopravných úsekov a s týmto procesom spojenými finančnými záťažami. Následne je dôraz kladený na dynamickú konfiguráciu.

Časť zhnutia výsledkov z experimentálnej časti obsahuje porovnanie vylepšení prístupov k riadeniu svetlenej signalizácie križovatiek. Prvotne sú statické optimalizačné prístupy porovnávané medzi sebou pre definíciu lepšieho statického prístupu na základe výsledných

meraných cieľov optimalizácie. Lepší z týchto prístupov je následne porovnaný s dynamickým prístupom optimalizácie.

Formou vizuálnej reprezentácie je demonštrovaná postupná optimalizácia meraných cieľov vrámci jednotlivých optimalizačných prístupov.

Simulácia zvoleného dopravného uzlu ukázala pozitívny vplyv aktualizácie zastaralých križovatkových plánov na merané ciele. Ukázalo sa, že rozdiely v meraných cieľoch medzi dynamickou konfiguráciou a dobrou statickou konfiguráciou nie sú až také diametrálne. Z tohto dôvodu je odôvodnené pri výbere formy optimalizácie dbať viac na iné aspekty spojené so zvolenými prístupmi pri procese rozhodovania. Nakoľko očakávané rozdiely medzi dvomi prístupmi vrámci finančného zaťaženia na vykonávajúcu autoritu sú veľmi odlišné, je namieste adekvátna analýza cien príležitostí. Nakoľko však informácie ohľadom finančných zaťažení nie sú verejne dostupné, ide len o ich odhad a rozdielny medzi prístupmi môžu byť bezvýznamné.

Keywords
Average Daily Traffic, Road Capacity, Traffic Intersection, Rush Hour, Traffic lights, Traffic collision

Klíčová slova
Priemerná denná premávka, Kapacita cesty, Križovatka, Dopravná špička, Svetelné signalizačné zariadenia, Dopravná nehoda

Reference
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Management of Traffic Lights

Declaration

I hereby declare that this Bachelor's thesis was prepared as an original work by the author under the supervision of Ing. Josef Strnadel Ph.D.. I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

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Adrián Piaček
May 27, 2020

Contents

Chapter 1

Introduction

As the number of cars on the roads had increased exponentially over the last few decades [7], traffic has become one of the most pressing matters of the dense urban areas. Not only is it frustrating to be stuck at the traffic congestion, it also deteriorates the air quality in these major urban areas. Traffic management is an extremely complex problem, with many conflicting goals and challenges. One of the most fundamental of these challenges occurs at the intersection, where multiple streams of traffic cross their paths. Traffic is mostly controlled by traffic signs and traffic light signals. Both of these create an interrupted traffic flow. Reason why traffic lights are so popular is that they offer commendable balance to considerations needed when controlling traffic. These include relatively low implementation cost, small space requirements, but most importantly the ability to handle large amounts of traffic with only some interruptions. On the other hand simple traffic signs are capable of handling only up to medium amount of traffic.

The fact that can not be overlooked is driver's capabilities, humans have by nature low attention spans and inadequate reaction times, that often cause traffic discoordination. Phenomenon is highly visible at the intersections where drivers are expected to accelerate their vehicles at the exact moment traffic light signal changes color. Nevertheless, due to the driver's limitations mentioned above, cars entering the intersection accelerate individually rather than simultaneously, thus creating a limit to the overall throughput of an intersection. Unsurprisingly, this is one of the problems that can not be solved in the foreseeable future, as it is unrealistic to expect drivers to be completely taken out of the equation just yet. Even though self-driven cars are no longer an unthinkable luxury, we are still far away from completely changing whole transportation infrastructure to only support driverless concept. It is believed, that if all traffic is controlled by artificial intelligence, hence the simultaneous acceleration at intersections is the practice at place, then traffic efficiency would be improved by a significant margin at all intersections worldwide. In the ideal situation, intersections would not cause any interruption to the traffic flow whatsoever. Another possibility of this concept is to get rid of intersections entirely. After all, traffic light controlling is just a tool for drivers to communicate with other lanes to establish an order of entry to the intersection.

At this point in time, intersections controlled by traffic lights are the limit to the maximum throughput of the roadway, in other words increasing the number of lanes or speed limit will not have great impact on the overall capacity of the road. This is due to the fact that the demand for roads far outstrips supply, so if the capacity of the road doubles, so does the amount of people using the road. Drivers will just adjust to any change in road capacity.

Whole transportation infrastructure is focused around safety and efficiency. The only way to increase the number of vehicles, safely travelling from point A to point B is to increase the efficiency of the intersection. Therefore, the main objective of bachelor's thesis is centered around the monitoring and manipulation of traffic lights at the intersections. Specifically to explore techniques, that limit build up of queues and minimize time spent at the intersection. Moreover, all of the mentioned objectives need to follow principles declared and accepted by the Vienna Convention on Road Traffic from 1968 [4]. Rigid normalization of intersections is also crucial, so when road user comes to an unfamiliar intersection, he implicitly knows his role and can act accordingly.

Chapter 2

Preliminary study

2.1 Modeling and Simulation

System

The system is a collection of elementary parts, elements of a system, which have ties with each other.

Modeling

Modeling is a process, whose objective is to create a model.

Model

A model on the other hand is an imitation of a system with the use of a different system. A model is similar to, but simpler than the system it represents. If the model is created with the higher overall complexity, experimenting with a model becomes far more difficult. For that reason it is essential to identify important parameters of a modeled system and with the use of an abstraction other less essential parameters are omitted. Models can surely reach very complex representation of reality, but expansions in complexity should be applied iteratively.

Generally, model classifications include [12]:

- deterministic (input and output variables are fixed values),
- stochastic (at least one of the input or output variables is probabilistic),
- static (time is not taken into account),
- dynamic (time-varying interactions among variables are taken into account).

Typically, simulation models concerning transportation are stochastic and dynamic.

Model's time

It is a timeline of a model, simulates real time from real system. During the simulation may not be synchronized with the real time.

Abstract Model

Abstract model is an abstraction of a real and working system of interest. Abstract model is very similar to the system it represents, yet simplified to the extent that still supports a close approximation to the real system and incorporate most of its salient features. Between real system and abstracted model is homomorphic relationship.

Homomorphic relationship

Homomorphic relationship during conversion from real system to an abstract model allows for an abstraction. In other words, omission of the unimportant elements, with element assignment in the ratio N:1. Between the elements contained inside abstract model equivalent relationships are to be kept, same as in the real system.

Simulation Model

The term simulation model illustrates an abstract model that is written in a form of a computer program. Between abstract model and simulation model exists isomorphic relationship.

Isomorphic relationship

Isomorphic relationship during conversion from an abstract model to the simulation model requires assignment of system elements in the ratio 1:1. Additionally, it requires equivalence of relations between elements.

Model validation

An important issue in modeling is model validity. Model validation is an effort to showcase that all experiments are carried out with a model equivalent to modeled system. Model validation techniques include simulating the model under known input conditions and comparing model output with system output. It is not possible to ensure total parity, thus model validity is comprehended as the degree of accuracy of obtained results.

Model verification

Verification of a model means that the isomorphic relationship between the abstract model and the simulation model is checked.

Simulation

Simulation is a process, where thanks to application of input parameters into the simulation model, feedback can be gathered from a model. Analysis produces results, that can be compared to the values from a real system. By that model can be validated as mentioned earlier or furthermore input values could be configured to achieve proper validation.

An objective of a simulation is to gather new knowledge about modeled system. Simulation over testing in a real system is usually sought out when experimentation with a real system is not possible. Advantages as well as disadvantages are closely connected. As a result of reduced complexity of a modeled system situations can be simulated faster that in the real system. Due to the possibility to change input parameters more optimal solution or configurations can be found. On the other side of a spectrum, disadvantages can not be overlooked as real system is simplified to various extents. Many parameters are not taken into consideration as they were considered less essential. Nonetheless, as the parameter selection is only based on the assumption, omitted parameters may carry much more importance to the overall model than expected. This works also other way around with essential parameters that may come out as less vital than expected.

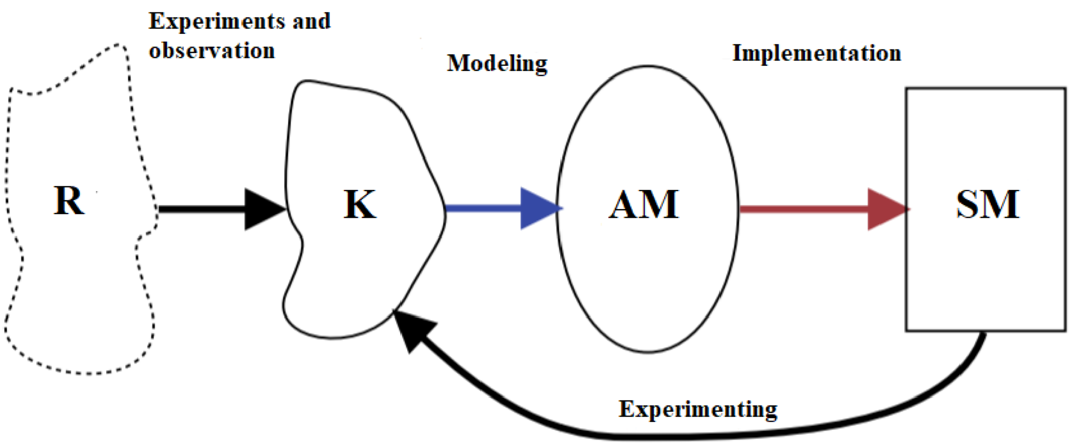


Figure 2.1: Reality - Knowledge - Abstract model - Simulation model [15].

Figure 2.1 illustrates whole process of gaining new knowledge about a system with the use of simulation.

2.2 Transportation infrastructure

Road User

Anyone who uses a part of a traffic node is considered road user. Roads accommodate many distinct road users, including pedestrians, motorcycles, bicycles, large trucks, buses and farm machinery. Road users have to cooperate in order to keep traffic moving safely and efficiently.

Vulnerable Road Users

Vulnerable road users are defined as „non-motorised road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility and orientation“ [5]. Efforts should be made to ensure that the needs and preferences of vulnerable road users are taken into account when designing a transportation infrastructure.

Road Safety

Road safety is characterized by the absence of accidents, such as road collisions between road users. It is measured by number or collision or rather its expected number at a given time. There has been a serious concern about road safety since the start of the automobile age. It is uniformly accepted, that there are many costs associated with vehicular mobility. These include air pollution, noise, collisions and so on. However, the most alarming are economic and social costs associated with collisions as these greatly exceed other costs due to the pain, loss of property, injury and deaths associated with them. Approximately 1.2 million people are killed in traffic collisions each year worldwide [2].

Traffic Intersection

A location where the multiple roads intersect, allowing vehicular traffic to change from one road to another. Traffic intersections are divided into two categories. Controlled and uncontrolled traffic intersections. Additionally, traffic intersections are prone to occurrence of most serious traffic accidents and collisions. This is due to the nature of vehicular traffic flows at the traffic intersection, that are often directly opposite.

Controlled intersections have traffic lights, yield signs or stop signs to control traffic.

Uncontrolled intersections have no signs or traffic lights. They are usually found in areas where there is not much traffic. In order to establish a system for traffic control if two vehicles come to an uncontrolled intersection from different roads at the same time, the driver on the left must let the driver on the right go first. This is called yielding the right-of-way.

Traffic Collisions

Traffic collision refers to a situation where a vehicle collides with another road user, animal, road debris, or other stationary obstruction or building. Traffic collisions occur due to one or as a combination of multiple of the three components of the road system. Three components are drivers, vehicles and road environment. Minimization of road accidents is achieved by the road safety enhancement programs. More than 90% of collisions involve driver mistake or complacency [2]. From this statistic, it could be assumed that road safety enhancement programs should focus mainly on drivers. This is achieved by establishment of legislative rules and penalties, supported by publicity of information to increase driver awareness. Since human error contributes mostly to crash causation, it ought to effectively address the problem by educating and training the road user to behave better.

Yet driver focused enhancement programs may not be the most cost effective solution to safety problems. Improved safety of a road can be achieved by an advanced road engineering, that would allow for fewer driver mistakes. This relatively recent commitment is more and more frequently applied across the world to ensure traffic safety. There are various approaches for advanced road engineering.

Self-explanatory Roads

If a road design is complex, it may cause an uncertainty in driver decision making. Drivers could have difficulties to choose the appropriate speed or to choose a proper lane in a timely manner. A self-explanatory road is a road designed and built in a way that it induces adequate behaviour and thereby less driving errors are expected. The road design parameters promote the correct behaviour of road users on these roads.

Roundabouts

Roundabout is a traffic intersection at which traffic moves in one direction around a central island to reach one of the roads converging on it. Roundabouts are popular option not only to increase efficiency, but most importantly to reduce fatality of crashes appearing at the intersections. Due to the drivers imperfection, intersection is still prone to occurrence of fatal crashes. Advanced traffic signal management plans can significantly reduce number of these collisions, but can not get rid of them. Fatal crashes are very often caused by frontal collisions, whereas these occur rarely at the roundabout as traffic flows are not directly opposite. Crashes, even fatal ones can still appear, but side collisions are much more common.

Traffic Lights

Signaling devices positioned at road intersections, pedestrian crossings and other locations to control competing flows of traffic are called traffic lights. They are eligible to replace traditional traffic signs, that offer lower traffic throughput than traffic lights do.

Nowadays traffic lights are very common at places where multiple streams of conflicting traffic cross their paths. They play an important role in the transportation network and are the source of significant public frustration, when not operated efficiently. It is estimated that many of traffic signals could be improved by upgrading equipment or simply by updating the traffic signal management plans. Outdated or poor traffic signal timing accounts for a significant portion of traffic delay on urban roadways. Traffic signal reconfiguration is one of the most cost effective methods to improve traffic flow and to mitigate congestion.

A traffic signal that is properly designed and timed can be expected to provide one or more of the following benefits [18]:

- Provide for the orderly and efficient movement of people.
- Effectively maximize the volume movements served at the intersection.
- Reduce the frequency and severity of certain types of crashes.
- Provide appropriate levels of accessibility for pedestrians and side street traffic.

Traffic lights phases

Important information that can not be omitted, for in depth understanding of experiments presented in this bachelor's thesis, is the manipulation of traffic lights phases.

Typical four-way intersection offers road user the possibility to choose from three directions called movements. Right and through are usually grouped together, whereas left movement stands alone. Thus typical four-way intersection has eight vehicular and four pedestrian movements. These movements are typically grouped into phases of traffic light signals. Left turn movements of opposite approaches can be grouped into the same phase, because they can both enter typical four-way intersection at the same time without any conflicts and little restrictions. Stated intersection usually consists of four consecutive phases repeated in periodic cycle.

Figure 2.2 showcases periodic cycle of light signal phases for typical four-way intersection. As mentioned in previous paragraph left turns are usually grouped into the same phase, these are represented by phases `A` and `C`. Whereas grouped movements for straight and right vehicular flows are represented by phases `B` and `D`. Additionally, phases `B` and `D` also implement all of the pedestrian movements on a typical four-way intersection. Figure 2.2 illustrates pedestrian movements as dotted arrows, while vehicular movements are illustrated as standard arrows.

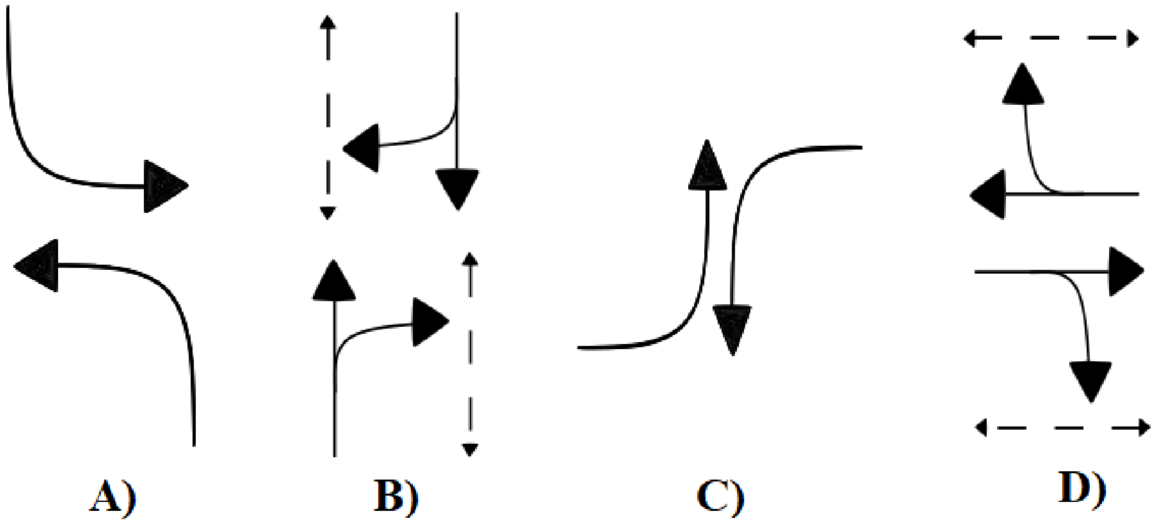


Figure 2.2: Light signal phases for typical four-way intersection.

Important to realize is that 2 phases are a minimum amount that is allowed on the intersection with traffic lights, otherwise there is no need for traffic signaling at all. Traffic situation with less than two phases would be either called a roundabout or a simple turn.

Moreover significant amount of analysis and consideration must go into the intervals for each sequence of a phase. Ideally a green light should be long enough to clear the queue that was built up during the red light. This is not always possible, especially at the peak times on busy intersections.

Signal timing often requires tradeoffs between various road users at the intersection. These tradeoffs could result in competing ideas, such as longer time duration for pedestrian crossings versus maximizing automobile capacity handled by an intersection.

Traffic Signal Management Plan - (TSMP)

The traffic congestion is largely caused by inadequate road usage due to a lack of traffic management. Traffic signal management plans encapsulate configurations of traffic light phases used for particular traffic node. An appropriate traffic signal management plan is essential for safety and smooth traffic flows on roads, hence making a maximum usage of roads to enlarge the current road capacities. The plan describes the objectives of traffic signal management within the context of the set range of goals.

The traffic signal management plan should target one or multiple of following enhancements:

- Reduce traffic related crashes.

- Minimize the rates of travel and waiting time.
- Increase road capacity.
- Improve traffic flow and air quality in urban areas.

Static traffic lights signaling

Technology has advanced and is constantly evolving, undeniably for this branch of studies as well. Dynamically controlled intersections are still far outmatched in numbers in comparison with statically controlled intersections. Static traffic signaling refers to a situation, where phases of traffic lights are allocated with a fixed time duration. Under fixed time configuration, the traffic signals display green to each approach for the same number of seconds every light cycle, regardless of traffic conditions.

There are two main ways to configure static traffic lights. Firstly, where lengths of phases are invariant and secondly variant lengths of traffic light phases. This differentiation is based on manners in which traffic lights are adapting to the change of estimated traffic volume for specific time period.

Invariant phases of static traffic lights

First category deals with fixed intervals for every phase throughout whole monitored time frame. Time for the specific phase is set and immutable. More often than not, TSMP needs to be configured to specifically satisfy requirements of peak-hour complication, as these have the highest impact on overall waiting and travel time. As a result length of phases remain the same, regardless of lower expected traffic volume during other time periods. This prerequisite makes optimization more of a compromise.

Variant phases of static traffic lights

The second way to configure statically operated traffic lights is to set different variations of traffic light phases for specific time periods. And by doing so, this approach mimics dynamic traffic light configuration to some attainable extent. Usually different lengths of traffic light phases are used for distinction between week days and days during a weekend. As demand for roads lowers, the adaptation to intervals of traffic light phases is needed, otherwise unnecessary waiting time happens. Thus interval that would normally be considered ideal, is inaccurate during weekend. This is due to the fact that lanes are not occupied as highly as would typically be.

Dynamic traffic lights signaling

On the other side of the spectrum is a dynamic traffic lights signaling. Traffic data such as traffic volume, speed of incoming traffic can now be gathered by sensors or cameras. Thus traffic light phases can rapidly adapt to real-time traffic conditions to reduce traffic congestion.

These sensors are often referred to as the detectors. The detector is an equipment, that has the ability to prolong or shorten particular traffic phase. These can either be loops buried in the carriageway or above ground detectors which are often mounted on the top of the signal poles. The loop detectors give a precise location of vehicles passing or occupying the loops, but the prediction of the vehicle dynamics is limited by the detector locations. Detectors shall not be confused with the tools used as an automatic enforcement by the police or other authorities.

In contrast with statically operated traffic light phases, implementation of dynamic traffic light phases is estimated to be very expensive as advanced technology is required. Hence if setting up whole intersection with new equipment for real time traffic monitoring is in fact expensive, it makes financial sense to focus firstly on most problematic streets. The intersection can consist of both statically and dynamically configured traffic lights.

Practice of Treating Left-Turns

Left turns are one of the most dangerous driving maneuvers and account for the majority of traffic collisions occurring on the roads. When drivers make a left turn, they are required to make a series of quick, but crucial judgments. In a short amount of time, drivers must evaluate the speed and distance of incoming vehicles, watch for the incoming lanes to be clear, and make sure they have enough time to make a turn before the light changes. All that while paying attention to their other surroundings. Since the left-turning volume is normally smaller than that of straight movements, usually only one or no lane is assigned exclusively for left-turns.

There are several methods of treating left-turns. Among these the most common way is the `unprotected left-turn` in which no signal time is assigned to left-turns. The opposite case is adopting exclusive left-turning phase, known as `protected left-turn` [16].

Unprotected left-turns

Vehicles make a left-turn through a gap in the opposing traffic. In order to make an unprotected left-turn at a signalized intersection, the vehicle should advance into middle of the intersection and wait for adequate gap, that can be utilized. If the vehicle can not find any gap in the opposing traffic, it completes its turn during the yellow interval of a phase.

In order to make a left turn, the driver has to decide whether to take or reject the gaps in the opposing traffic. This is not an easy task especially for inexperienced drivers.

Protected left-turns

Normally protected left-turn is indicated by signal with an arrow pointing to the turning direction. To allow protected left turns from all approaches at a typical four-way intersection, a light signal cycle should be distributed into four phases. This will roughly halve the throughput of an intersection in comparison with a light signal cycle with unprotected left-turn. Moreover, the adverse effect on vehicle delay is much more serious.

2.3 Software overview

There are many possibilities to opt to when looking for a sufficient software to simulate traffic in. Understandably there are various aspects that differentiate these software options. The first overall facet of decision making process was set to concern the availability of the software for simulation. Some of the simulation software options were on paper better match, but offered only limited functionality in the free package version, thus would not make the latter cut. Further highly valued aspects were configuration options of vehicle behaviour and traffic lights phases.

PTV Vissim

Whether comparing junction geometries, analyzing public transport priority schemes or considering the effects of certain signaling, PTV Vissim allows the user to simulate traffic patterns exactly [1]. For many PTV Vissim is considered to be one of the world's leading software for traffic simulation. It offers display of all road users and their mutual interactions. Any level of complexity is manageable in PTV Vissim, thus is a powerful tool for the evaluation and planning of urban transport infrastructure. PTV Vissim offers a bit more flexibility than other contenders because of its ability to model unusual sites as well as providing powerful 3D and movie capture. Nonetheless, for my bachelor's thesis this functionality is not groundbreaking. Furthermore PTV Vissim traffic simulation software is easy to use without a need for scripting.

It uses vehicle-driver-units that incorporate several stochastic variations. Thus, there are not virtually two vehicles that have the same driving behaviour. PTV Vissim is being continuously developed to provide up to date driving behaviour. PTV Vissim has over 40 years of experience in the transport strategy and traffic solutions industry [1]. Extensive documentation and training programs, professional customer service and support team, are all very good attributes that were considered.

The major setback, resulting in not electing the PTV Vissim, was the fact that it is license limited software, meaning that it supports only small spatial range and thus might not be the best fit for the bachelor's thesis and its consecutive improvements and traffic node scaling.

Aimsun

AIM SUN software allows you to model transportation networks in both small and large scales, from a single intersection to an entire region. It is mostly used for the assessment and optimisation of traffic signal management plan and bus transit schemes. Nevertheless, further challenging tasks such as toll and road pricing, safety analysis or work-zone management could be simulated in Aimsun as well.

One of Aimsun's most outstanding features is its speed, simulator is the fastest on the market by far. This is achieved by multithreaded software architecture. According to Aimsun web page: „Even on a laptop, the Aimsun simulator can run a model of the whole Singapore with 10,580 intersections and 4,483 km of lanes 2-3 times faster than real time. [17]".

Aimsun has a mouse-based user interface, simple click and drag to build an intersection is enough or double-clicking on an object to edit its attributes. It is divided into few licensing categories, but in this case free academic version would be enough to build a model up to 100 nodes and 200 kilometers of lanes.

Additionally, Aimsun's rich traffic management framework is capable of simulation of a model network operation that may have an impact on driver's route choice:

- parking schedules,
- cleaning schedules,

- reversible lanes,
- dynamically reserved lanes [17].

Aimsun is an excellent option if project's scale rapidly expands in the future, but limitation in free version poses a possible setback.

Tritone

Tritone is a micro-simulator for road networks developed by the University of Calabria as an innovative tool for simulation of a traffic flow. It is totally free of charge, but requires license requesting and the scan of identity card. Tritone is able to represent in a timely manner, precise and specific traffic simulation and its evolution. It takes into account the geometrical aspects of the infrastructure and the real behaviour of drivers. Tritone can simulate signalized intersections, but is insufficient for roundabouts and extensive public transport simulation [3].

Tritone calculates emissions, created by a passing traffic flow, what is another great indicator of a burden caused by traffic. In a similar fashion, also calculates gas consumption, thus might be excellent to use when carbon footprints are focus of the study in the future.

Tritone returns the results in an analytical form, based on control intervals defined by the user. Firstly in graphic 2D form, developed for computers with low performance to expand its range of compatible hardware. Secondly in 3D form for more pleasant and accommodating view of the simulated network.

That all being sad, graphics and the user interface of the simulation software are considered average or rather mediocre at best when compared to other contenders.

SUMO - Simulation of Urban Mobility

SUMO [10] is a free open traffic simulation software that was developed in 2001. Since then evolved into a full featured software suite for traffic modeling. SUMO is capable of reading different source formats and routing utilities from various input sources. Two major design goals are approached, software shall be fast and it shall be portable. Hence, SUMO's model can be easily transferred to other software in case of specific utility requirements, that can not be provided by SUMO.

SUMO allows modeling of intermodal traffic systems including road vehicles, public transport and pedestrians. Also has extensive visualisation tools. SUMO provides extensive scheduling of traffic lights. These can be either imported or automatically generated by the SUMO itself. Thus SUMO offers excellent functionality for management of traffic light phases as well as baseline option for enhancement comparison. All traffic lights are generated with a default cycle time of 90 seconds [11]. Its 3D graphics are a bit underwhelming, on the other hand it offers format support for previously mentioned simulation software PTV Vissim, which supports up-to-standards 3D modelling in case of future project expansion.

In comparison with its competitors, there are no limitations in the network sizes and number of simulated vehicles, supplying an option to overload traffic node. SUMO is not only a traffic simulator, but rather a suite of applications which help to prepare and to perform the simulation of traffic. It is more frequently used as microscopic traffic simulator, but for my bachelor's thesis is surely sufficient. Furthermore, it allows the usage of faster data structures, each adjusted to the current purpose, instead of using complicated and ballast-loaded ones. Additionally, supports visual appearance changes of all traffic road users, what is extremely valuable when minimizing the time needed for a repeated complex simulation.

SIMLIB

SIMLIB was developed in 1991 at the Faculty of Information Technology, Brno University of Technology.

„SIMLIB/C++ is simple SIMulation LIBrary for C++ programming language. You can create models directly in C++ language using simulation abstractions and tools from the library. SIMLIB allows object-oriented description of continuous, discrete, combined, and various experimental models." [14]

SIMLIB library eases up description of the model directly in C++ language, thus compiler for simulation language is not needed. Advantages include a possibility to use simultaneously standard means of programming from C/C++ language as well as SIMLIB library. On the other hand, one of the disadvantages that could be considered before opting towards SIMLIB library is an inability of additional syntactic and semantic checks, that could be done by simulation's compiler. For easier description of models, that require description by differential equations initial SIMLIB library was amplified by addition of 3D abstraction.

That all being said, SIMLIB is limited when it comes to convertibility to another software option, that might be significant defect in future project expansion.

Uppaal Stratego

Uppaal Stratego is a branch of the Uppaal family of software tools, additionally it belongs into the free licensing category for non-profit use, evaluation, research and teaching purposes.

Uppaal is an integrated tool environment for modeling and simulating extended with data types. Validation and verification of real-time systems modeled as networks of timed automata is also possible in Uppaal. The tool allows for efficient and flexible strategy-space observation before final implementation by maintaining strategies as first class objects in the model-checking query language. [13]

Uppaal Stratego combines machine learning and model checking techniques to synthesize near optimal control strategies. It has been applied successfully to several studies, such as battery optimization in satellites, safe and optimal cruise control and optimal floor heating controlling. [6] Thus Uppaal Stratego can be used to learn strategies for complex systems, in this case controlling the traffic lights at the intersection.

CORSIM

The CORSIM traffic simulation model was originally developed for the Federal Highway Administration in the middle of 1970s.

CORSIM is an extensive traffic simulation package, that was developed to model surface roadways, highway systems as well as combined networks with simple or more complex control conditions. The advantages of the CORSIM lie in its ability to simulate a wide variety of traffic conditions from signalized arterial corridors and highway corridors to controlled intersections with the use of traffic lights. [9]

The fact that can not be overlooked as it plays an important role in selection of software for this bachelor's thesis is documentation. CORSIM is one of the best documented simulation tools available, due in large part to the continued validation and updating that has occurred over nearly 50 years of existence.

Lane changing parameters must be carefully coded in CORSIM because they can have a large impact on network performance. The unrealistic lane changing behaviour can create excessive travel delays where they should not exist. [9] The impacts of lane changes will be less apparent under low density conditions, but as roadway conditions approach capacity the impacts on a verity can be substantial.

Chapter 3

Selected problem and means to solve it

3.1 Chosen software option

For this particular bachelor's thesis, decision was made to use simulation software SUMO, or rather Simulation of Urban Mobility. It provided the best compromise when all requirements were taken into consideration. This chapter introduces various instruments used during model creation and consecutive simulation. Aim was set to reach more optimal configuration of traffic light phases that would improve traffic fluency and other important characteristic explained in following chapters. The source of the majority of information in this chapter is SUMO's documentation [11].

Following SUMO components are mainly used in this bachelor's thesis. Road networks which allow to model the relevant part of the map or in this case chosen traffic node, containing roads, lanes and intersections. Vehicles which allow to realistically model the traffic demand. Traffic lights which allow to model a signalized intersection. Induction loops which indicate if a car is on the given detector.

Road networks

Firstly, SUMO road networks are encoded as XML files. The contents are grouped by the instances in the following order:

- edges, each edge contains the list of lanes that belong to it,
- traffic light logic,
- junctions, representing the area where different streams intertwine,
- connections, describing which outgoing lanes can be reached from an incoming lane,
- optionally roundabouts.

Vehicles

Secondly, vehicles are explicitly defined at least by an identifier, departure time and route through the network. Other details are just optional, but can be very helpful when creating a complex traffic simulation. SUMO also supports emission calculations as each of the vehicles can be assigned to one of the available pollutant or noise emission classes. A single vehicle is not modeled, it is always the vehicle on a journey. Meaning that, once a vehicle has reached its destination, it is deleted from the system and cannot be referenced any longer.

SUMO provides an option to create repeated vehicular flows inside of a simulation. In this scenario definition of vehicles slightly differs. At first vehicle type is defined and encapsulated inside of a `vType` element. And only after that specific flows are created and encapsulated inside of a `flow` element.

Source code shown in Listing 3.1 presents an example of the vehicle type definition.

```
<vType id="example" accel="5" decel="7.5" maxSpeed="15"/>
```

Listing 3.1: Example of vehicle type definition.

- Attribute `id` represents the identification of particular vehicle type.
- Attributes `accel` and `decel` illustrate a maximal rates of acceleration and deceleration that particular vehicle type can accomplish.
- Attribute `maxSpeed` provides boundary on maximal speed of a specified vehicle type.

Subsequently Listing 3.2 showcases source code used for definition of the repeated vehicular flow.

```
<flow id="carflow" type="example" vehsPerHour="10" begin="0" from="e0"
to="e2"/>
```

Listing 3.2: Example of repeated vehicular flow definition.

- Attribute `id` represents the identification of particular vehicular flow.
- Attribute `type` specifies vehicle type defined inside of the `vType` element with the same `id` attribute.
- Attribute `vehsPerHour` specifies number of vehicles inserted into a simulation each hour. Vehicle departure is defined by a number of vehicles in a flow that is thereupon distributed equally in the given interval.
- Attribute `begin` represents time in a simulation since flow starts to be active.
- Attributes `from` and `to` illustrate vehicle route in a traffic network.

At the given departure time the simulation tries to insert the vehicle into the simulation. If this is not possible because it would result in a collision, the simulation retries in the next simulation step. Hence simulates waiting traffic queue, that is especially purposeful during peak-hour congestion.

There are multiple additional attributes for the vehicle definition, that as mentioned may help when creating a traffic node with higher complexity. These include `Vclass`, `minGap`, `emergency deceleration` and `sigma`.

First of all, `Vclass` or in other words vehicle class, used as differentiation tool in SUMO. Value represents abstract vehicle class inside SUMO applications. `VClasses` are used to either allow or disallow the usage of lanes for certain vehicle types. Carbon dioxide emissions are also different for contrasting `VClasses`. Important to comprehend is the fact that these are abstract, so they offer no restriction policy. Henceforth, during implementation manual safeguarding of other attributes is required. Otherwise, the traffic flow could have ended up with half metre long buses or cars that are four times longer with unrealistic acceleration rate.

Second of all, `minGap`, value represents minimal space requirement between vehicles that is set to be followed by drivers, while standing at the intersection as can be seen in Figure 3.1.

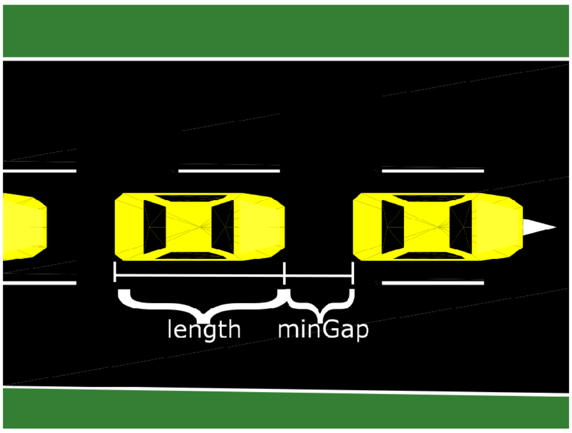


Figure 3.1: MinGap and length differentiation [11].

Value shall not be confused with required distance during a travel on a roadway, as this value is derived from speed limitation on that portion of a road.

Third of all, `emergency deceleration`. In addition to the deceleration rate that vehicle has on regular basis, this value represents the highest possible deceleration rate vehicle can achieve in case of an emergency braking to avoid collision. Technologies such as anti-lock braking system, that help decelerate vehicle in a safer manner, are not taken into consideration, as these are outside of SUMO's modeling possibilities.

Last of all, `sigma`, value simulates driver's imperfection as a decimal value with lower extreme at 0 and higher extreme at 1, where 0 denotes perfect driving.

Traffic Lights

Thirdly, traffic light signaling. SUMO supports multiple ways to generate traffic light signals. Either statically generated traffic light signals or dynamic traffic light signals used together with various advancements in technology on a road to provide real time information concerning traffic.

Both of these ways need to be encapsulated inside of a `tlLogic` element, but differ in attribute `type`. Properly functioning `tlLogic` elements requires initial set up of various attributes. These include already stated `type`, but also attributes `id, programID` and `offset`.

- Attribute `type` is used for differentiation between dynamic and static traffic signal control logic at the intersection.

- Attribute `offset` provides an important functionality of traffic light coordination of adjacent traffic intersections.
- Attribute `id` represents means of identification for specific intersection inside a complex traffic system that `tlLogic` is assigned to.
- Attribute `programID` represents identification of particular traffic signal control logic. As one intersection can use multiple `tlLogic` elements.

Source code showcased in Listing 3.3 presents encapsulation of `tlLogic` for typical static four-way intersection with just 2 phases of traffic lights.

```
<tlLogic id="junction_example" type="static" programID="1_0" offset="0">
    <phase duration="20" state="GrGr"/>
    <phase duration="15" state="rGrG"/>
</tlLogic>
```

Listing 3.3: Example of tlLogic definition.

Each phase is defined at least by an attribute `duration` combined with attribute `state`. Attribute `duration` is simply time interval during which specified phase is active. Whereas attribute `state` establishes, which movements have during a duration of particular phase priority to enter the intersection and which are in opposition prohibited to enter. Each character within a phase's state describes the state of one signal of the traffic light.
There are four main characters used.

- Character `'r'` representing red light for a signal. Instructing vehicles to stop and wait.
- Character `'y'` representing yellow light for a signal. Instructing vehicles to decelerate if they are far away from the junction.
- Character `'g'` representing green light without priority for a signal. Vehicles may pass the junction if no other vehicle from higher priority stream uses the junction, otherwise they must decelerate to let it pass first.
- Character `'G'` representing green light with priority for a signal. Vehicles may pass the junction.

Figure 3.2 illustrates a situation at a typical four-way intersection, where the current state of traffic lights is `"GrGr"`. The leftmost letter `'G'` encodes the green light for edge `0`, followed by a red light for edge `1`, green light for edge `2` and red light for edge `3`.

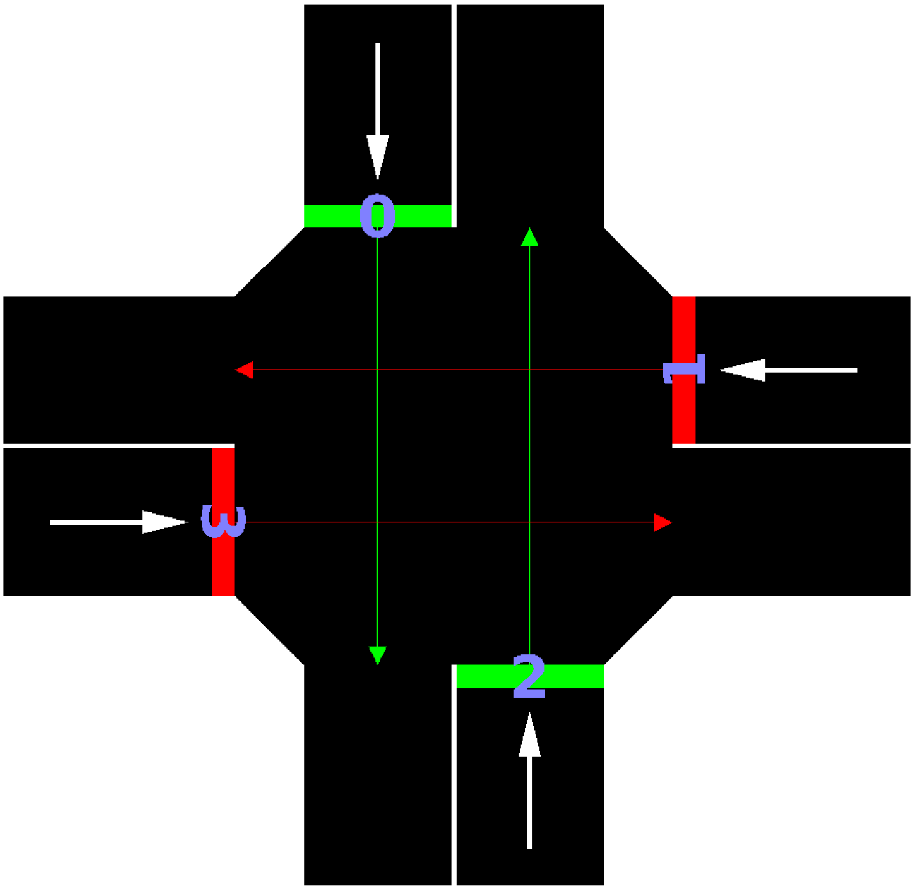


Figure 3.2: State of traffic lights at the typical four-way intersection.

In SUMO statically generated traffic light signaling is defined by the attribute `type` with its value set to `"static"` coupled with the set duration for each phase.

On the other hand, dynamically generated traffic light signaling is defined by the attribute `type` with value equal to `"actuated"`. It is coupled with addition of both `minDur`, in other words minimal duration of a green phase, as well as `maxDur`, in other words maximal duration of a green phase. These are considered extremes for each green phase as the duration is extended or truncated correspondingly to a demand and will not exceed these values under no circumstances.

For proper functionality of dynamically set traffic lights additional equipment is needed. Detector is an essential part of dynamically set traffic intersection and has its own set of modifiable parameters. First of all `max-gap` describes the maximum time gap between consecutive vehicles of an incoming traffic flow, causing the current phase to be prolonged. Nevertheless, only in range of its limitations provided by `minDur` and `maxDur`. Next is `detector-gap`, value represents distance measured in seconds between the detector and the end of lane, where traffic light is mounted on. In reality detectors are also used to adapt to changes in pedestrian flows, unfortunately SUMO does not support this advancement in technology just yet.

SUMO supports numerous TSMPs for the traffic intersection inside a simulation, but these need to have explicitly defined order of switching policy. Likewise all need to be encapsulated into `WAUT` element. For proper functionality of `WAUT` element additional attributes such as `startProg` and `refTime` need to be declared. Listing 3.4 showcases an implementation of the `WAUT` element.

```
<WAUT refTime="0" id="wautJunction_1" startProg="0_0">
    <wautSwitch time="19801" to="0_1"/>
    <wautSwitch time="28801" to="0_2"/>
    <wautSwitch time="50401" to="0_3"/>
    <wautSwitch time="59401" to="0_4"/>
</WAUT>
```

Listing 3.4: Example of WAUT element definition.

Attribute `startProg` is used to declare the plan for controlling traffic lights that will be used at the beginning of the simulation. whereas attribute `refTime` represents reference time which is used as an offset to the switch times. Each `WAUT` element needs to contain `wautSwitch` statements that define chronological order of switching policy for multiple plans. Aditionally, these `wautSwitch` statements contain their own attributes, such as `time`, that determines since when is particular plan active, and also attribute `to`, which on the other hand determines what plan is next in line in switching policy.

Surely with a complex traffic node there may be multiple `WAUT` elements and no rules by which TSMP would be assigned to the particular traffic intersection. Because of that in SUMO also exists element called `wautJunction`. This element contains attribute `wautID` coupled with attribute `junctionID`. Listing 3.5 showcases an implementation of the `wautJunction` element.

```
<wautJunction junctionID="junction_example" wautID="wautJunction_1"/>
```

Listing 3.5: Example of wautJunction element definition.

Attribute `wautID` specifies `WAUT` element and attribute `junctionID` specifies identification of intersection that `WAUT` should be assigned to.

Output Information

All information about the state of traffic at specific simulation time as well as measured objectives is gathered in form of simulation output. SUMO includes simulation output through generating output files. All output files written by SUMO are in XML format by default.

In this bachelor's thesis decision was made to focus on specific edges, thus opting to edge based traffic measurements. Values inside of this output describe the situation within the network with the use of macroscopic values such as the mean vehicle speed, the mean density, the waiting time.

3.2 Model of the system of traffic lights management

As mentioned above, it is essential to firstly identify essential parameters of a real system before implementation. In case of traffic these can be divided into multiple categories, such as drivers and their driving behaviour, vehicles and their limitations, traffic node and lastly elements of traffic management.

For drivers factor such as driving proficiency is considered. When it comes to vehicles their physical capabilities need to be established, such as acceleration, deceleration as well as their physical dimensions. Description of traffic node needs to contain information about each part, such as length, estimated traffic volume and so on. Lastly and most importantly elements of a traffic management that represent main target of my bachelor's thesis. These can be various types of signaling equipment, road signs or other detection devices.

For establishment of a reasonable scale for the thesis, decision was made to focus on specific traffic node consisting of four-way intersection directly connected to the T-type intersection.

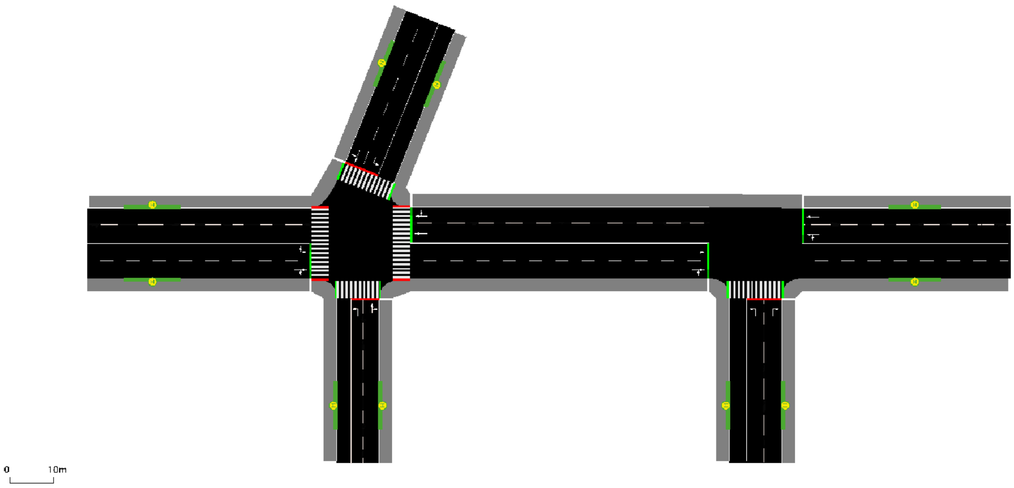


Figure 3.3: Model of the chosen traffic node.

This type of an intersections, from Figure 3.3, was chosen due to the fact that it is very common type of intersection in urban areas and mostly occurs right outside the main perimeter of the city center [19]. Meaning that majority of employed population must pass this type of the intersection on daily basis in order to safely travel from work, in the city center, to their homes in further parts of the city. Thus creating a peak-hour complication.

Furthermore, this traffic node is excellent to showcase necessity of adjusting intervals for each phase of traffic lights signaling. Objective of this bachelor's thesis is to eliminate traffic congestion caused during various time periods and limit rate of waiting time needed for daily commute. The ulterior motive of the simulation is to simulate a realistic peak-hour complication. For that reason a specification of an abstract city center was established, located on the south-west side of a model. Therefore traffic in the morning is more directed towards south-west, meanwhile traffic in the afternoon is directed out from south-west towards other parts.

Traffic node decomposition

Chosen traffic node is composed of 12 edges, more commonly known amongst the majority of population as streets. These count up to 19 lanes of vehicular traffic and 12 lanes of pedestrian movement, all connected to one of two junctions. Edges incoming towards the intersections are consisting of 2 vehicular lanes, whereas outcoming traffic from the intersections is merged into one lane, with the exception of edges between junctions.

As can be seen in Figure 3.4 length of all lanes is set at 80 metres, except the ones between two intersection, for whose decision was made to use 120 metres long lanes. Together with intersections whole traffic node corresponds to 3.07km of usable roads.

On all horizontal edges decision was made to use lane assignment that supports `unprotected left-turns`. There were two main reasons why `unprotected left-turns` were used. This lane assignment provides increase in throughput of the traffic intersection. But also because traffic is often focused towards specific cardinal direction rather than equivalent from each approach. Thus gaps in traffic are frequent and can be utilised by drivers.

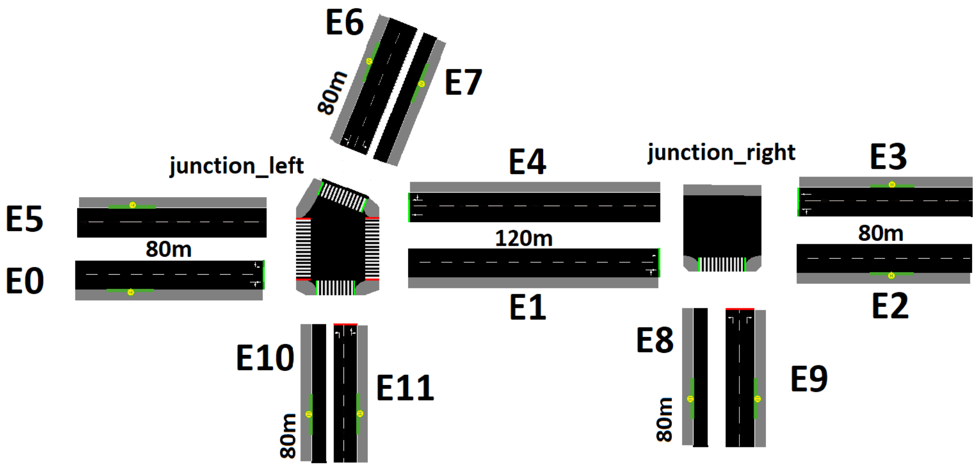


Figure 3.4: Decomposition of the chosen traffic node.

Furthermore, all edges contain bus stop for accurate simulation of public transport, once again except the edges between two intersections. In this case placing a bus stop between two intersections would result in unnecessary bus stoppages and make light coordination of two traffic intersections significantly more difficult. Buses are required to wait at all bus stops on their route for duration of 10 seconds. Duration is immutable and based on carried out calculations during peak-hour complications at the city center in Brno. Length of all bus stops is equal to 20 metres as outlined in Figure 3.5.

Widths of pedestrian and vehicular lanes differ as shown in Figure 3.5. Sidewalk lanes are rarely so generously allocated in the real worlds scenarios. Yet this is more of a security precaution against a pedestrian flow jamming during attempts to overload the intersections. Further explanation is provided in Section 4.2. Figure 3.5 also illustrates width of all pedestrian crosswalks for the chosen traffic node.

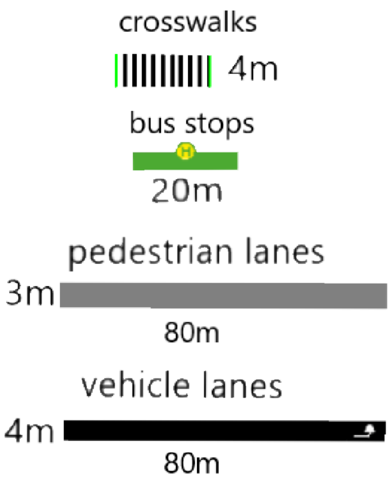


Figure 3.5: Differentiation of traffic node elements.

Each intersection could be represented as its own isolated entity, when in reality each signal is a component of larger traffic network. Each component of a traffic network can have an impact, from time to time a significant one, on other components in the system. Chosen intersection is a classic example of such system as it consists of two signals closely spaced in a row on a major roadway. If light signal for a particular vehicular flow at one intersection changes to green, but other light signal for the same flow does not vehicles can back up. In the extreme cases as shown in Figure 3.6, cars can sit at the intersection for multiple light cycles without possibility to pass through until the light beyond clears. Thus reducing capacity and throughput of an intersection.

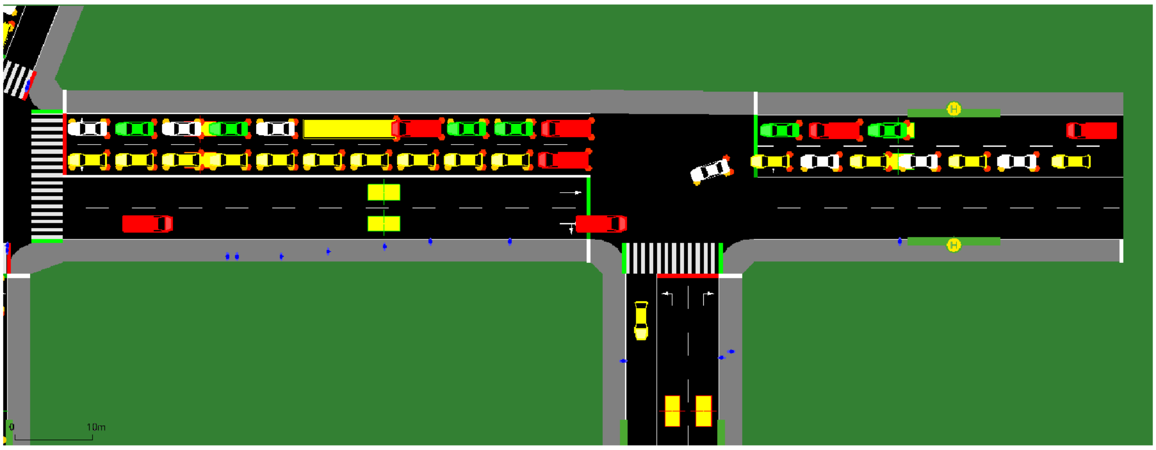


Figure 3.6: Traffic congestion caused by a signal discoordination.

One of the solutions to this problem is signal coordination. Light intervals are not only considered at one specific intersection, but also the status of nearby signals is taken into account. This type of signal coordination can significantly enhance the volume of traffic, that can pass through a traffic network. Nevertheless, this type of solution only works on the parts of traffic network, that do not have other sources of traffic interruptions, such as driveways, turns to businesses or adjacent parking slots.

In the best-case scenario whole traffic network is adaptive to the traffic demands. Of course it would require real time monitoring of a traffic network, otherwise would not be able to adapt accordingly.

Chapter 4

Implementation

4.1 Traffic demand

Once traffic network is established, vehicles driving on the roads shall as well be generated. This is called the traffic demand. In spite of few applications that can be used to define vehicular demand for SUMO, manual definition of traffic demand was chosen. This is for the sake of obtaining information from multiple traffic scenarios, ranging from a directing of traffic to a maximum overload of a traffic node. All that while keeping number of average daily traffic constant during repeated simulations.

Once vehicle is inserted into the simulation, the model calculates new speed of a vehicle and either accelerates or decelerates the vehicle accordingly.

$$v' = (v + a * t) \tag{4.1}$$

New velocity of a vehicle v' is calculated by use of an equation (4.1), where:

- v is the speed of a vehicle from previous simulation step,
- a is a constant acceleration of vehicle type,
- t is a length of a step.

Throughout the simulation vehicles are constantly changing their position on the traffic node.

$$s' = \left(s + v * t + \frac{a * t^2}{2} \right) \tag{4.2}$$

New position of the vehicle s' is calculated by use of an equation (4.2), where:

- s is the position of the vehicle from previous simulation step,
- v is the speed of the vehicle from previous simulation step,
- a is a constant acceleration,
- t is a length of a step.

In this bachelor's thesis decision was made to introduce multiple types of road using vehicles as well as pedestrian movements to appropriately simulate real world scenario. Vehicular types were chosen based on information provided by European Statistical Office (EUROSTAT), concerning road traffic volume distribution: "Road traffic volumes were dominated by passenger cars. In all countries, for which data were available, over 59 % of the total road traffic was conducted by passenger cars in 2009. The volumes of traffic by goods road vehicles fluctuated between an 11 % share of the total in Slovenia and a 39 % share in Cyprus. The shares of buses and coaches were significantly lower; the highest was recorded in Latvia (2 %)." [7].

There are total of 3 passenger vehicle types present, as these are most common. In addition to that public transit as well as freight transport signify for one vehicular class each. All of these have its own attributes outlined in Figure 4.1. Due to the fact that whole traffic node is defined in metres and SUMO itself carries calculations out in metres or metres per second, implicit configuration is kept and outlined.

ID	----	CarA	CarB	CarC	CarD	Bus	----
color	----	red	green	white	yellow	yellow	blue
Vclass	----	delivery	private	passenger	taxi	bus	pedestrian
maxSpeed	[m/s]	15.278	15.278	15.278	15.278	15.278	1.39
accel	[m/s]	2.6	2.6	2.6	2.6	1.2	1.39
decel	[m/s]	7.5	7.5	7.5	7.5	4	2
emerg. decel	[m/s]	9	9	9	9	7	----
minGap	[m]	3	3	3	3	3	0.25
sigma	----	0.5	0.5	0.5	0.5	0.5	----
length	[m]	6.5	4.3	4.7	4.3	12	0.215
width	[m]	2.16	1.8	1.9	1.8	2.5	0.478
height	[m]	2.86	1.5	1.73	1.5	3.4	1.719

Figure 4.1: Definition of the model's road users.

Additionally, to the attributes shown in Figure 4.1, that are considered self-explanatory such as acceleration, deceleration, maximum speed of a vehicle, length and so on. There are a few that need to be explicitly defined to ensure uniform understanding of these user types. These include `Vclass`, `minGap`, `emergency deceleration`, as these were already explained in Section 3.1, necessary to introduce are only specific values for each of the attributes.

As presented in Figure 4.1, `minGap` for all vehicles amounts to the value of 3 metres, what is half a meter longer than implicit value generated by SUMO. Reasoning behind elongating minimal gap is to ensure travel safety rather than solely focusing on efficiency of the intersection. The exception for uniform `minGap` are pedestrian flows. Pedestrian are unique category as they use their own lanes and interrupt the traffic flow only at the crosswalks. Nevertheless, are enlisted in attributes overview as they are part of traffic system.

Figure 4.1 also enlists values of `sigma`, in which mediocre value of 0.5 was set in order to introduce some random driver's behavior, but to be still reasonable enough to experiment with. If higher extreme would be chosen to simulate total driver imperfection, it would have indirectly violated Vienna Convention on Road Traffic, which states following: “Even if traffic light signals authorize him to do so, a driver shall not enter an intersection if the density of traffic is such that he will probably be obliged to stop on the intersection, thereby obstructing or preventing the passage of cross traffic.” [4]. And thus with unpredictable driving behaviour safe passage could not be ensured.

Listing 4.1 shows the source code containing definition of vehicle type used during simulation in SUMO. Specifically vehicle type `CarA` presented firstly in Figure 4.1, which corresponds to delivery vehicles mostly used for transport of goods and product.

```
<vType id="CarA" accel="2.6" decel="7.5" maxSpeed="15.278" sigma="0.5"
minGap="3.0" guiShape="delivery" vClass="delivery" color="red"/>
```

Listing 4.1: Definition of freight transport vehicle type.

Other vehicle types are implemented in a similar fashion with unique values for every vehicle type.

4.2 Time frames

Simulation is carried out inside of a one day period, with an intention to include all possible traffic flow rates. Thus simulation is divided into five smaller time periods corresponding to different times during a day. Each of them is focused on diverse traffic load. These five smaller periods are not independent, meaning that when there is a congestion of traffic, traffic flow would be carried onto the following period as an extra increase in traffic for that period. Main ambition is set to overload the traffic node at specific time frames to showcase how subsequent changes to traffic signal management plan would affect the measured objectives, if they were to be implemented into real world situations. With this in mind, average daily vehicular traffic loaded during the simulation of one day is 29509 with addition of 9578 pedestrians loaded throughout the simulation. Demonstrating an amount high enough to overload the chosen traffic node.

Pedestrians have different goals throughout the simulation, varying from being only a small addition in numbers and interruptions, to having a massive impact on overall system. Nonetheless, one precondition remains invariant throughout all time periods. All crosswalks must be used at least to some extent, otherwise pedestrians are just visual addition to the simulation, but do not carry any additional worth for simulation purposes.

As was already stated, SUMO works with seconds as primary physical unit for majority of calculations, thus one day is represented as 86400 seconds divided into five categories corresponding to the chosen hourly format.

0:00 (00000) - 5:30 (19800)

The first time period is defined as one of the most quiet ones, with only 1258 vehicles loaded in a span of five and half hours, due to the effort to resemble reality. Most of the employed population uses this time during a day to reset and recharge, hence are not at the streets nor intersections. However, some traffic is still established. On the other hand, traffic is not directed towards any specific cardinal direction, for this reason all car flows embody same amount of vehicles per hour. Figure 4.2 presents hourly distribution of car flows from specific edges(`E3, E0, E6, E9, E11`) to their final destination, defined as the end of specified edge during the time period 00:00 - 5:30.

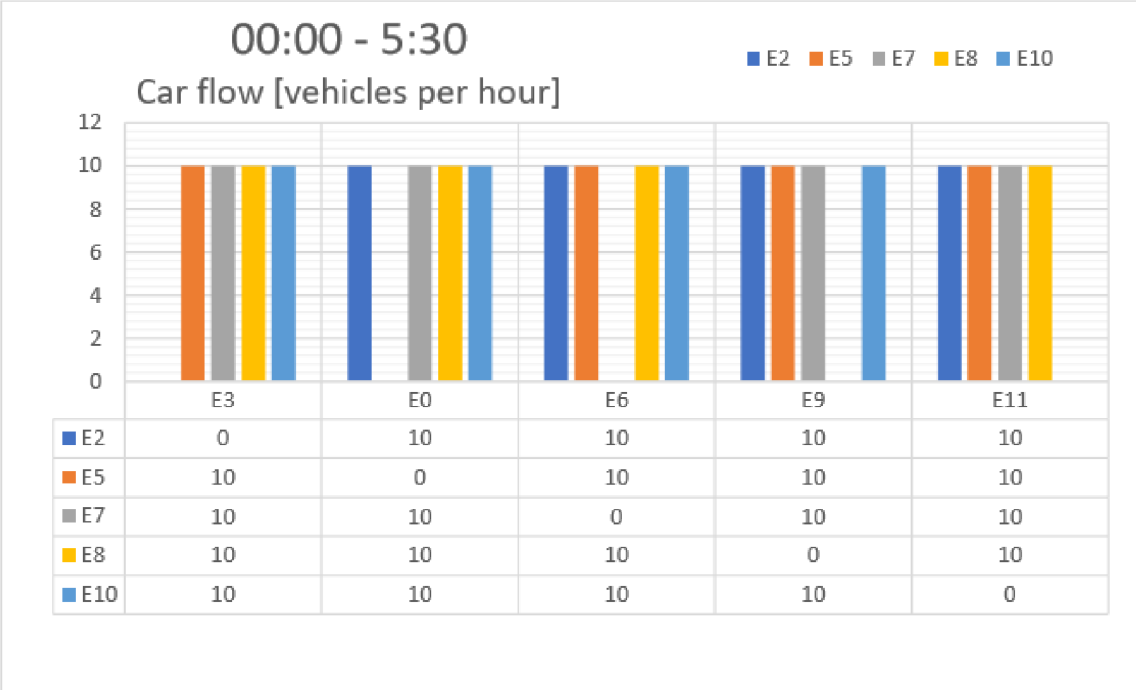


Figure 4.2: The car flows during 00:00 - 5:30 the time period.

Public transport follows the same logic, that can be encountered as a practice already at place at city of Brno during nights. All buses leave the stations at the same time from city center, firstly at midnight and every half hour after that. Whereas public transport from outside the city center is, in comparison with previous one, delayed by half an hour on its first ride, but follows same transit schedule afterwards.

Pedestrian movement is also adjusted to be similar to normal human behaviour with only 198 people loaded in the five and half hours span period, divided into six pedestrian movements distributed to move through all defined crosswalks.

5:31 (19801) - 8:00 (28800)

Next one on the list is the time period when majority of employed population is travelling to work and so traffic is adapted to this scenario. Traffic flow from parts outside of the city is tripled in comparison with the traffic flow from the city center. This successfully overloads the traffic network with 6454 vehicles, from which 2429 vehicles are still stuck at the waiting queue to even get to the intersection and towards their final destination. These will be inserted into the simulation during the next time period as an aftermath of a rush hour.

Similarly public transport is compacted in a way, that bus flows towards city center are happening every 6 minutes, whereas bus flows out of the city center are happening only every 20 minutes. In an attempt to further resemble reality, buses from the same direction are delayed by two and half minutes, as it is not common to have transit schedule with exactly same departure times for different public transport lines. This policy of delaying transit lines is established in every time period, with the exception of the first one, which follows its own logic.

Figure 4.3 presents hourly distribution of car flows from specific edges(E3, E0, E6, E9, E11) to their final destination, defined as the end of specified edge during the time period 5:31 - 8:00.

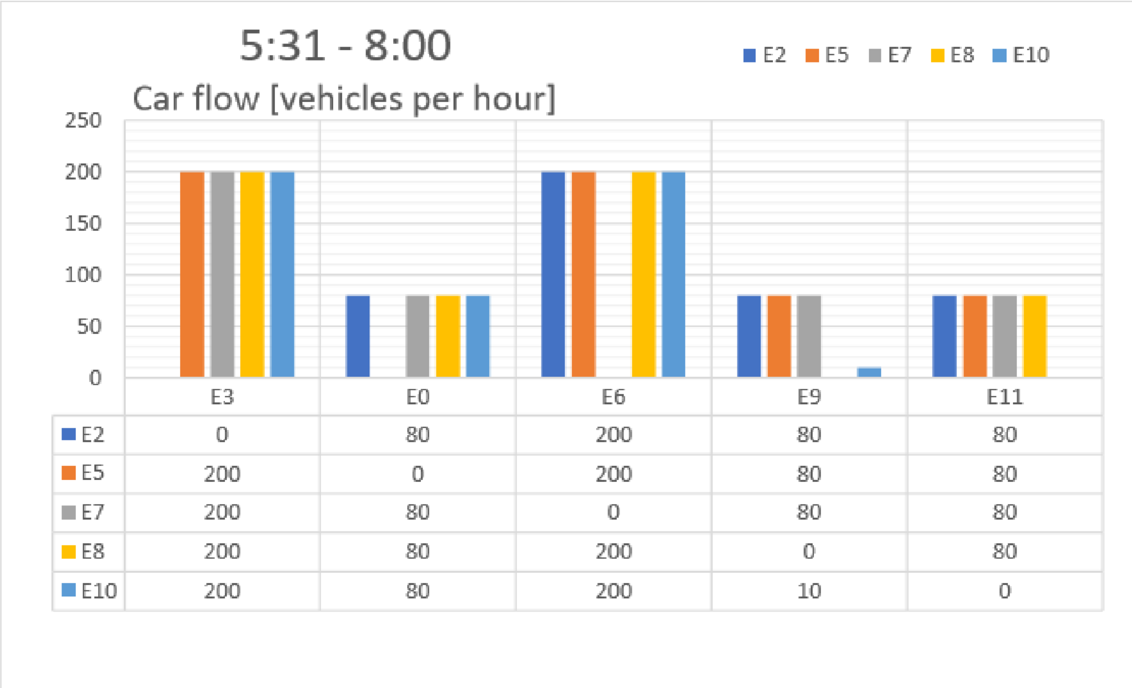


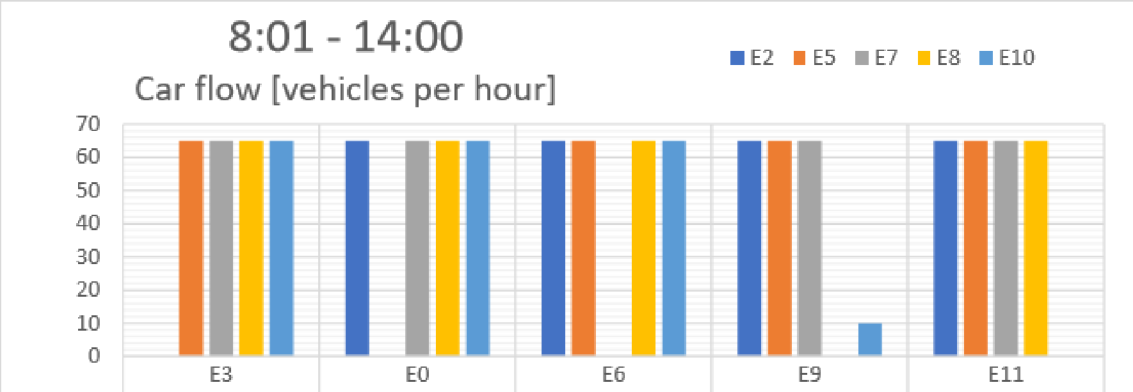
Figure 4.3: The car flows during the time period 5:31 - 8:00.

Another key point, pedestrian movements follow similar logic, thus all movements are heavily targeted towards south-west, fictional city center, what causes intentional overwhelming of the traffic node. During this period sum of 1000 pedestrians is loaded into the simulation, divided into five pedestrian movements, each at 80 people per hour.

8:01 (28801) - 14:00 (50400)

Equally important is period from 8 in the morning to 2 in the afternoon, even though it is not considered to be a rush hour. Traffic node is still indeed cluttered with 7781 vehicles in addition to the aftermath of previous rush hour. Period is essential for correct operation of many small businesses, transportation companies or self-employed people. In comparison with already multiple times mentioned rush hour complication, traffic flow during this time period is not directed towards definitive cardinal direction. Nor is public transport compacted in any cardinal direction. Bus lines are departed every 15 minutes without differentiation between starting position inside of a city center or outside of a city center perimeter.

Figure 4.4 presents hourly distribution of car flows from specific edges(E3, E0, E6, E9, E11) to their final destination, defined as the end of specified edge during the time period 8:01 - 14:00. Volumes of the traffic flows are implemented to be equal. With the exception of the traffic flow from edge E9 to the edge E10, as its primary function is just to create overload between two intersections. Inadequate load on this route could cause whole traffic node to be shut down.



	E3	E0	E6	E9	E11
E2	0	65	65	65	65
E5	65	0	65	65	65
E7	65	65	0	65	65
E8	65	65	65	0	65
E10	65	65	65	10	0

Figure 4.4: The car flows during the time period 8:01 - 14:00.

Number of pedestrians is lowered to 30 people per hour in all six pedestrian movements, whose numbers sum up to 1080 people loaded into the simulation in a span of almost six hours. Hence this time period is more focused on vehicular transportation.

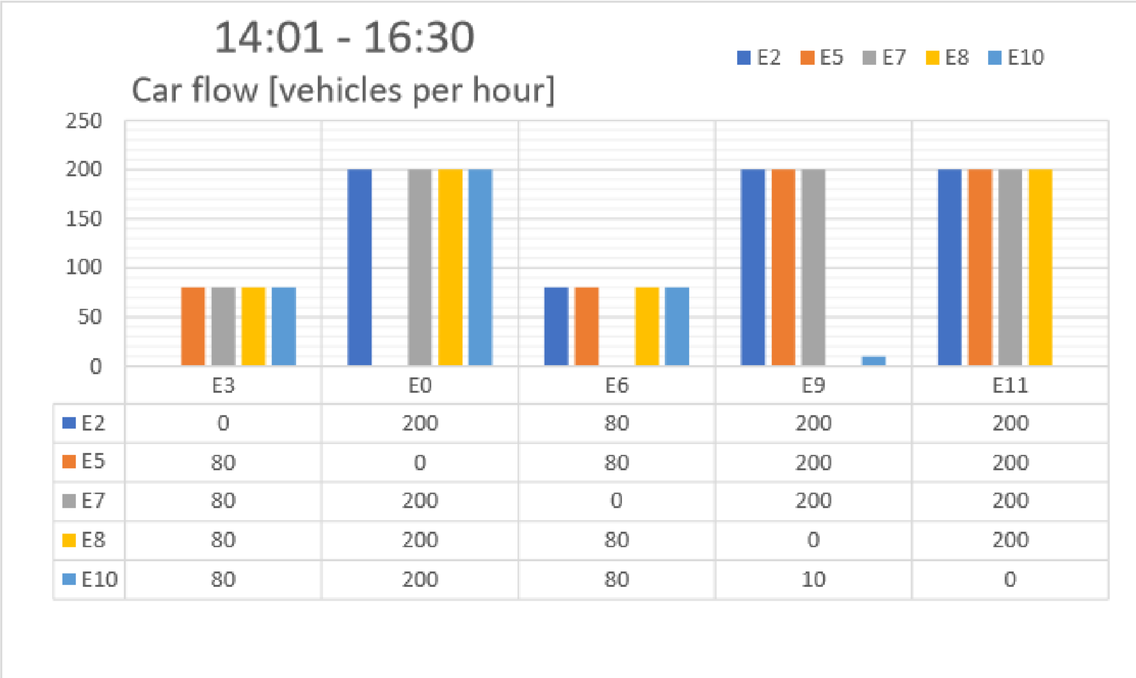
14:01 (50401) - 16:30 (59400)

Not the last one, nevertheless very important is the second appearance of the rush hour complication. Whereas this one is directed from south-west, fictional city center, rather than other way around. Rush hour is created due to the fact that employed population is travelling from work, in the city, to further parts of the city. Further parts of the city are represented by edges `E7` and `E2`, but also edge `E8` to simulate traffic overload.

Traffic flow from the city center is tripled in comparison with the traffic flow towards the city center to adequately demonstrate overload during specific phases of traffic lights. That is achieved by the insertion of 7376 vehicles during a span of less than two and half hours, from which 2343 vehicles are still stuck at the waiting queue to even get to the intersection and towards their final destination. Similarly public transport is compacted in a way that bus flows out of the city center are happening every 6 minutes, whereas bus flows towards city center are happening only every 20 minutes.

Number of pedestrians is once again enhanced to 80 per hour in five pedestrian flows, whose number sum up to 1000 people loaded into the simulation in a span of almost two and half hours. With an intention to direct the pedestrian flows out of the city center.

Figure 4.5 presents hourly distribution of car flows from specific edges(`E3`, `E0`, `E6`, `E9`, `E11`) to their final destination, defined as the end of specified edge during the time period 14:01 - 16:30.



	E3	E0	E6	E9	E11
E2	0	200	80	200	200
E5	80	0	80	200	200
E7	80	200	0	200	200
E8	80	200	80	0	200
E10	80	200	80	10	0

Figure 4.5: The car flows during the time period 14:01 - 16:30.

16:31 (59401) - 23:59 (86400)

The last implemented time period is essential due to the fact that overload on traffic node from previous rush hour can have a consequence also after its estimated demise. Therefore provides opportunity to see influence on the density of a road. That can be very crucial identification of the traffic state.

Even though car flows were lowered in cars per hour that enter the simulation to only 6640 in a span of almost seven and half hours. This time period is used also to simulate overload with other road users, that to this point were a bit overlooked concerning their impact on the traffic flow, pedestrians. In this time period number of pedestrians entering the traffic network is almost doubled from each selected direction up to 140 people per hour in six separate directions. What resulted in overload on crosswalks and sidewalks with number as high as 6300 people loaded into the simulation.

Main aspiration of this approach is to create a situation where private vehicles and public transport are of a secondary importance. Replicating a situation where sport event, concert or any other mass gathering is taking place. Thus pedestrians slow or at some cases totally shut down the traffic for some time at these areas. Coupled with the fact that aftermath of a rush hour is still rapid, traffic node becomes significantly overwhelmed.

Figure 4.6 presents hourly distribution of car flows from specific edges(`E3`, `E0`, `E6`, `E9`, `E11`) to their final destination, defined as the end of specified edge during the time period 16:31 - 23:59.

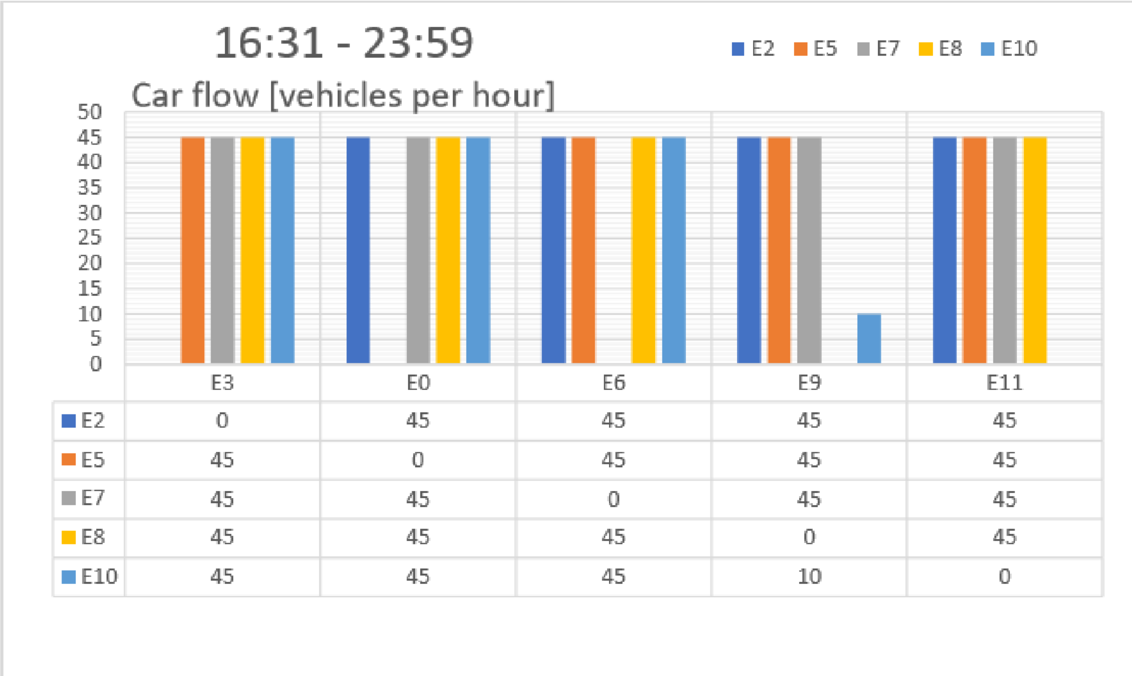


Figure 4.6: The car flows during the time period 16:31 - 23:59.

4.3 Traffic lights phases

Intersection `junction_right` of the chosen traffic node originates from `T-type` intersection. Hence a flow of vehicular transport could be tucked just into two phases of traffic lights, repeated in its own periodic light cycle. This approach would be sufficient in places with very low pedestrian movement. Because only then, vehicles turning right coming out of edge `E1` could proceed with almost no additional delay required to clear a crosswalk or to clear the intersection caused by backed up crosswalks.

Nevertheless, more common way to organize traffic light phases for `T-type` intersection, also used in this bachelor's thesis is to add an additional phase. Additional phase allows vehicles from previous phase to continue without interruption, but restricts pedestrians from a previous phase to enter the intersection until the next light cycle. Important point to realize, between these phases light remains green for the vehicular movement. Whereas light signal changes to a red phase for pedestrian movements only. Better understanding of a concept can be grasped from Figure 4.7, containing ring-and-barrier diagram for `junction_right`. Phases `"Right 1_1"` and `"Right 1_2"` illustrate differences between two almost identical phases, differentiated only by a restriction of pedestrian flows incoming into the intersection.

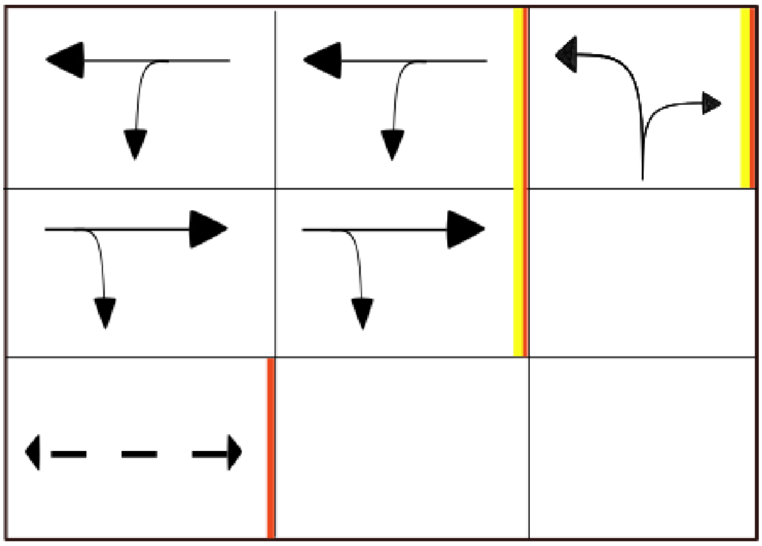


Figure 4.7: Ring-and-barrier diagram for junction_right.

Pedestrian light signal goes from green phase directly into the red phase and in the process totally skips yellow phase. That is due to the fact that traffic lights at the crosswalks do not need to signal incoming change of traffic light phase. Length of a yellow phase is calculated from the velocity of an incoming traffic stream. Be that as it may, speed of incoming pedestrian movement is low enough for the yellow phase to be entirely absent. Situation changes if crosswalks are supposedly used by bicycles as well as pedestrians, then yellow phase is often present.

Listing 4.2 illustrates the source code for implementation of traffic control logic at `junction_right`. As presented in Figure 4.7, ring-and-barrier diagram consists of 3 phases. Nevertheless, for proper functionality of simulation yellow phases also need to be enlisted.

```
<tlLogic id="junction_right" type="static" programID="1_0" offset="0">
    <phase duration="37" state="GGgrrrrgGGG"/>
    <phase duration="5" state="GGgrrrrgGGr"/>
    <phase duration="3" state="yyyrrrryyyr"/>
    <phase duration="42" state="rrrGGGGrrrr"/>
    <phase duration="3" state="rrryyyyrrrr"/>
</tlLogic>
```

Listing 4.2: Definition of default static traffic control logic for junction_right.

Intersection `junction_left` of the chosen traffic node simulates a situation where one of the lanes is used for both left-turns as well as straight vehicular movement. Thus number of phases could be minimized to count of 3 by clumping left-turns together with straight vehicular movement. As explained earlier, more common procedure is to add additional phases without pedestrian movements to prevent unwanted jamming at the intersection. Hence traffic signal management plan for `junction_left` is composed of 5 phases, presented in Figure 4.8 with the use of ring-and-barrier diagram.

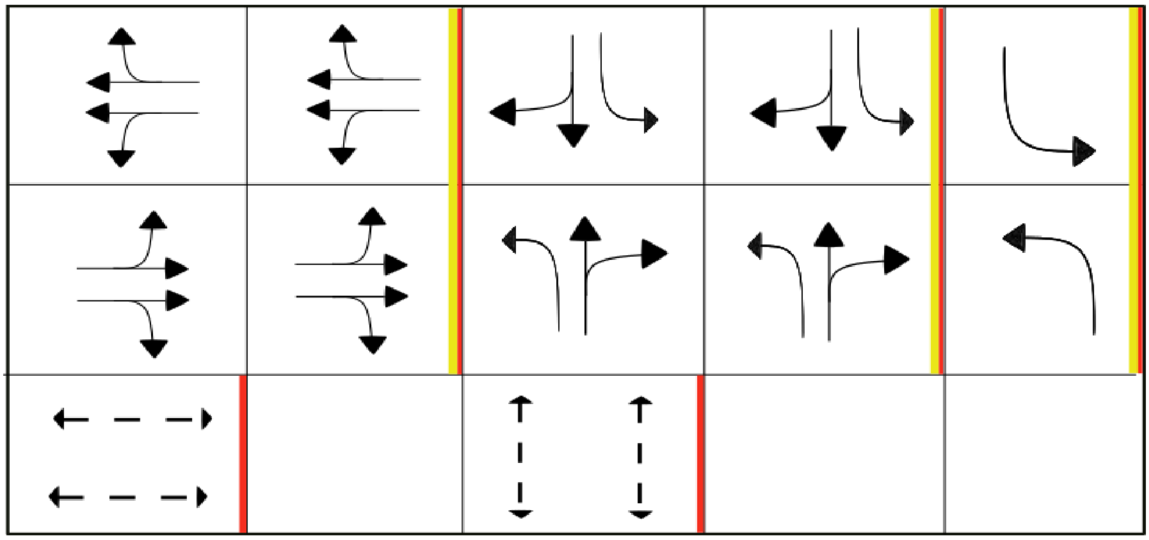


Figure 4.8: Ring-and-barrier diagram for junction_left.

In this unique situation, even if left-turns are grouped with other phases, there still needs to be one phase only for left-turns. Left-turns have lower priority than straight vehicular movements, which have right-of-way. Henceforth, vehicles waiting for their opportunity to pass the intersection can clump up the intersection and cause traffic congestion. To avoid this unwanted situation, intersection must be cleared off of these left-turning vehicles. That is done by addition of new traffic light phase. New phase does not need to be as long as other ones, yet can not be totally omitted.

Furthermore, the reason why only one left-turning phase is added, even though same problem may appear for the other approach, is that once again on horizontal edges isolated left-turns movement can not be done. That is due to the fact that horizontal edges support `unprotected left turns`, but vertical edges do not. This is true for both `junction_left` and in similar fashion for `junction_right`.

Listing 4.3 illustrates the source code for implementation of traffic control logic at `junction_left`. As presented in Figure 4.8, traffic control logic at `junction_left` consists of 5 phases. Nevertheless, for proper functionality of simulation yellow phases once again need to be enlisted as a part of `tlLogic` element.

```
<tlLogic id="junction_left" type="static" programID="0_0" offset="0">
   <phase duration="33" state="rrrrrgGGgrrrrrgGGgGrGr"/>
   <phase duration="5" state="rrrrrgGGgrrrrrgGGgrrrr"/>
   <phase duration="3" state="rrrrryyyyrrrrryyyyrrrr"/>
   <phase duration="32" state="ggGggrrrrggGggrrrrrGrG"/>
   <phase duration="5" state="ggGggrrrrggGggrrrrrrrr"/>
   <phase duration="3" state="yyyggrrrryyyggrrrrrrrr"/>
   <phase duration="6" state="rrrGGrrrrrrrGGrrrrrrrr"/>
   <phase duration="3" state="rrryyrrrrrrryyrrrrrrrr"/>
</tlLogic>
```

Listing 4.3: Definition of default static traffic control logic for junction_left.

Model's yelow phases of traffic lights

Yellow phases are calculated from maximum speed of incoming traffic and since maximum speed on whole traffic node is identical, all yellow phases are of a same length. Yellow phases are set by SUMO during initial definition of traffic node and are prearranged to be 3 seconds long for a model introduced in Figure 3.3. This configuration is thus kept throughout whole simulation.

4.4 Static traffic signaling

Static traffic lights are adequate in heavily congested areas. Nevertheless, if lightly trafficked side road is included within the traffic node, it can be very wasteful. During multiple time periods there is targeted discrepancy of vehicles waiting to enter the intersection, hence the time could be better allocated to a busier approach.

This can be one of numerous sources of frustrations, which drivers are facing when in contact with outdated static traffic signal management plans. While drivers are waiting on a red phase, opposite approach currently with green phase is empty. Sometimes static traffic lights are configured incorrectly, but more often than not, are at least somewhat outdated from times when traffic load was not as high as it is nowadays.

This is also true for static configuration used as a baseline for all improvements in this bachelor's thesis. Henceforth it is essential to set a record straight by firstly introducing statically operated intersections. Only after that proceed to newer and more complex solution for traffic optimization.

Static traffic signaling with invariant traffic lights phases

Introduction of updated TSMP with invariant lengths of phases can conserve large amounts of time for drivers. Nevertheless, it is reliant on the large sample size of information from which new TSMP needs to be derived. Even though, updated invariant phases could produce sufficient improvements in traffic throughput and reduction of waiting time, yet still would leave a leeway for further enhancements. Aberration is especially apparent during situations where increase in traffic volume is anticipated at specific days of month that are not in cohesion with an ordinary traffic volume. These may include mass people gatherings such as hockey games and similar sport, theatre events that occur on irregular basis.

Invariant phases of traffic lights are still very beneficial to use, if other consideration factors such as financial concerns or development and implementation periods are justifiable. Optimization of invariant phases of traffic lights is by far less comprehensively focused than its counterparts. Thus is more favourable option to opt to if time for optimization is limited and requires immediate response to a current situation. These may very well be situations with emergency protocols at place or other kinds of restriction polices, specific to a particular traffic node. As TSMP could not be accounted for these in advance.

Static traffic signaling with variant traffic lights phases

Static variant traffic lights are usually focused on differentiation between weekdays and days on the weekend as was explained in Section 2.2. In this bachelor's thesis decision was made to focus on more detailed structure. Henceforth rather than differentiating only between weekday and day on a weekend, work is focused on specific time periods during a weekday presented in previous section.

Needless to say, this approach requires analysis of vast quantities of data and can be much more time consuming to properly manage and develop. However, in specific situations is estimated to produce a reduction of the measured objectives that is comparable to dynamic modification.

4.5 Dynamic traffic signaling

Dynamic traffic signaling usually involves reconstruction to an existing traffic intersection and by doing so increases financial ordeal of the optimization. That is due to the fact that real time traffic monitoring is required to appropriately adjust phases of traffic lights. There are multiple ways to monitor traffic flow nowadays, first of which is also used during simulation in SUMO, the traffic detectors.

In SUMO even if an intersection is defined as actuated, phases with only attribute `duration` will have constant duration for a phase. By the same token SUMO supports gap-based actuated traffic control. This control scheme is common mostly in Germany [11] and works by prolonging traffic phases whenever a continuous stream of traffic is detected. Otherwise it switches to the next phase after detecting a sufficient time gap between incoming vehicles. This allows for better distribution of time among green phases and also modifies light cycle duration in response to changing traffic conditions.

Chapter 5

Optimization of traffic lights signaling

There is a pool of objectives to choose from when optimizing traffic lights signaling. These include travel time minimization, travel delay minimization, throughput-minus-queue maximization and so on. Correct selection of the objective function in signal timing optimization is vital, yet there is a gap in the knowledge of how to perform the selection [8]. Optimization of traffic lights in this bachelor's thesis had the total waiting time as an objective, or in other words travel delay. Objective was chosen as this is by far the most widely used objective function for signal timing optimization [8].

A solution for the problem requires tuning the timing of each traffic light phase in the network. Optimization methods generally aim to minimize waiting time of vehicles, and maximise the total traffic throughput of a given intersections. Optimization problems, such as this one, with a lot of variables and constraints are hard to solve analytically. Therefore for optimization purposes heuristic approach was used.

SUMO by default generates its own traffic signal management plan. In regards to the fact, that bachelor's thesis is not centered around real traffic node, but rather on a generalized traffic node, SUMO's default values are considered baseline output information. Hence any further enhancements are compared to SUMO's default configurations as well as previously the best configuration.

5.1 Heuristics

At first, promising results were to be found with the help of simple tests to justify heuristics, otherwise approach could not be used. Due to the fact that initial checks returned acceptable reduction in waiting time, subsequent experiments were in place. If following changes returned better results they were recorded and explored further. Otherwise different phase length was analyzed.

Keeping in mind the ring-and-barrier diagram for each intersection stated in Section 4.3, all intervals are decreased and increased to all potential lengths. If one light phase was increased following needed to be decreased to keep light cycle intact, unless other techniques are used. Important to mention is that values could not drop below reasonable rate, otherwise it would damage model's rational representation of reality. Reasonable rate refers for example to the time pedestrians need to cross an intersection considering their maximum walking speed presented in Figure 4.1.

Once satisfying optimization configuration is found using waiting time as the main objective, then other statistics are explored. These include average travel time of a vehicles throughout the simulation, average speed of vehicles and lastly density of the roads, presented as number of vehicles per kilometer of usable traffic lane. These are referred to as the measured objectives or the extended measured objectives throughout the bachelor's thesis.

5.2 Static optimization

As mentioned in Section 2.2, there are 2 optimization techniques that are applicable to an optimization of static traffic light signaling. In this bachelor's thesis both approaches were compared to showcase advantages each can bring as well as to establish limitations of each approach.

The first one, configuration with invariant lengths of phases through whole simulation. In other words, length of a green phase for a particular incoming vehicular flow from specific direction, for example on edge `E3`, is as long during midnight as it is during a peak-hour complication.

The second one, that was expected to return better reduction in measured main objective of the simulation, is technique of variant lengths of traffic light phases. This might be done according to an estimation before its initial application to a real traffic intersection and could be updated afterwards from data generated from traffic intersection. Financial concerns and differences between the two techniques are not studied due to the lack of publicly shared information on a subject. Thus all financial aspects mentioned are strictly subjectively estimated.

Default waiting time measured from SUMO's default configuration for the simulation of one day with fixed and invariant traffic light phases sums up to **1.32E+06** seconds. Value roughly converts into approximately **367** hours per each day that drivers spend waiting. Number is high mostly because intersections are not coordinated and light cycles are not optimized as can be often seen at the real intersections as well. Stated waiting time was used as baseline value all enhancements of TSMPs were compared to.

Static traffic signaling with invariant traffic lights phases

In this section, attention was directed towards the situation where only invariant lengths of static traffic light phases and its subsequent modifications are applied.

Pedestrian orientated model

Firstly, situation was explored, where pedestrians are equally assessed as are other road users. Meaning that green light phase on the crosswalks was configured as long as possible, but with an attempt to reduce the overall waiting time to its reachable minimum. Key fact that shall be stated, SUMO's default static configuration of a traffic light phases is also mostly focused on the pedestrians. Therefore changes to the default configuration might have caused some deterioration to the unmeasured objectives. Mentioned changes were induced by the reduction of traffic light phases, when pedestrians were allowed to enter the intersection. On the other hand, these changes were more directed towards increase of traffic throughput. Meanwhile keeping effects on pedestrians as low as possible. Strictly focus on the one type of road users, could result in significant inefficiency of traffic intersection.

Figure 5.1 showcases that by implementation of a few changes to the traffic light phases and offsets, the waiting time for traffic node was decreased to **1.13E+06** seconds. Representing the **14.11%** decrease in the model's waiting time. All of the mentioned changes were applied only onto the `junction_right`.

Subsequent changes were applied also to the `junction_left` and whole model underwent an adequate signal coordination. That produced notable drop in the waiting time equal to **1.09E+06** seconds. Representing total of **17.26%** decrease in the waiting time in comparison with its initial default value. Thus saving drivers **63.28** hours daily. Changes to `junction_left` did not improve preceding **14.11%** enhancement by a significantly high margin. Therefore, the modification of phases applied onto `junction_right` was assumed to be the main rationale of overall enhancements. Surely addition of the offset on `junction_right` created the light signal coordination of these two intersections.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	30.69	313.75	1.32E+06	5.57	90	90
7	29.56	302.21	1.22E+06	5.69	90	90
6	28.19	287.21	1.14E+06	5.71	90	90
5	28.29	287.69	1.13E+06	5.69	90	90
4	28.21	287.22	1.13E+06	5.72	90	90
3	27.95	284.10	1.10E+06	5.78	90	90
2	27.88	283.54	1.10E+06	5.78	90	90
1	27.86	283.39	1.09E+06	5.77	90	90

Figure 5.1: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP in pedestrian orientated model with invariant lengths of traffic light phases.

Results from Figure 5.1 revealed that even if traffic light phases have equal lengths through the whole simulation significant reduction of the measured objectives can be achieved by updating TSMP. That was done through targeting the best configuration for the time periods when traffic load is the heaviest. Not only is the waiting time as well as the travel time noticeably reduced, improvement was evident in other factors as well. Density of the roads was decreased by **9.67%**, thus allowing more vehicles to be added into a transportation infrastructure in the future if needed.

Vehicular orientated model

Secondly, situation was analyzed, where time for pedestrian road crossing was minimized to its limits. By this approach time intervals for vehicular movements are maximized to the extent that would not disturb pedestrians crossing a road.

The maximum speed of pedestrians, presented in Figure 4.1, coupled with number of lanes the crosswalk is crossing through were used for calculation of safe pedestrian passage through the traffic intersection. An average pedestrian was expected to need 11.5 seconds, approximated to 12 seconds to establish a small surplus, to cross the vertical crosswalks. And 8.6 seconds, approximated to 9 seconds, to cross the horizontal crosswalks presented in the model.

This configuration of invariant traffic light phases was very successful when it came to directing a traffic load compared to previous calculations. On the other hand, due to the overload of pedestrians during the last time period, it had its limitations and sometimes was not sufficient to transport every pedestrian in a timely manner. As was explained in section 4.2 the last time period was configured in the way, that would overload the crosswalks and thus this behaviour was expected.

Regardless, measured waiting time of **9.58E+05** seconds, presented in Figure 5.2, is still very promising and should be considered an apparent upgrade in notoriously high waiting time at start of the simulation. By focusing on vehicles rather than pedestrians **27.37%** improvement was reached. Notwithstanding the fact that all traffic light signals were statically set and remained invariant throughout whole simulation.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	30.69	313.75	1.32E+06	5.57	90	90
5	26.38	268.06	1.03E+06	5.83	90	90
4	26.42	268.61	1.03E+06	5.84	90	90
3	26.32	267.58	1.02E+06	5.84	90	90
2	25.82	262.27	9.77E+05	5.86	90	90
1	25.54	259.19	9.58E+05	5.92	90	90

Figure 5.2: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP in vehicular orientated model with invariant lengths of traffic light phases.

Important information to this point not stated, yet evident from the presented figures. Changes to TSMP, in both pedestrian orientated model as well as vehicular orientated model, needed to sum up to 90 seconds long light cycle on `junction_left` and in similar fashion on `junction_right`.

Static traffic signaling with variant traffic light phases

In this section, variant lengths of the static traffic light phases and its subsequent modifications were applied. For correct implementation of variant lengths of traffic light phases, it was necessary to analyze each time period separately. As a result of this analysis an appropriate configuration was found to help minimize a total waiting time for that period. Previous tendency of keeping light cycle lengths equivalent is now omitted and so further modifications and its consequences on the measured objectives are introduced.

Each section contains the best configuration for specific time period as well as the second best configuration to establish different paths during optimization of TSMP that could be taken. Overloaded vehicles or in other words vehicles that are still waiting in the queue, incapable of entering traffic node, were not taken into consideration during process of finding the systematic improvements for each time period.

Time period 00:00 - 05:30

As the traffic is at its minimum throughout the simulation during the time period 00:00 - 05:30, it seemed appropriate to target minimal possible lengths for phases of traffic lights right away. As can be seen in Figure 5.3, lengths of phases for `junction_left` were reduced to a possible margin, keeping only length of phase `"Left 1_1"` and phase `"Left 2_1"`. Phase `"Left 1_1"` corresponds to minimum value that pedestrians need to cross a vertical crosswalks and phase `"Left 2_1"` represents the time pedestrians need to cross the horizontal crosswalks.

Phases `"Left 1_2"` and `"Left 2_2"` were set to the minimal possible value of 5 seconds, this represents minimal time interval in seconds to ensure clearing of an intersection before allowing the next conflicting phase.

Additionally, phase `"Right 1_1"` was set to 12 seconds as this configuration provided better results than keeping minimal value of 9 seconds. This is due to the fact that `junction_right` contains only one crosswalk, thus all pedestrian movements incoming to the intersection pass only through one crosswalk resulting in higher pedestrian load. Waiting time was estimated to be furthermore cut down by addition of an offset on `junction_right`, however subsequent change did not provide any dramatic advancement.

	junction_left						*junction_right*			
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_1*	*Offset_right*
Default	33	5	32	5	6	0	37	5	42	0
2	12	5	9	5	6	0	12	5	8	0
1	12	5	9	5	6	0	12	5	8	5

Figure 5.3: Lengths of traffic light phases during the time period 00:00 - 05:30.

Figure 5.4 presents the measured objectives from the time period |00:00 - 05:30. Even though traffic volume was minor, reduction of the waiting time reached by modification of TSMP is **54.12%**.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	22.74	43.27	3.84E+04	5.50	90	90
2	16.44	31.85	1.78E+04	6.28	46	31
1	16.43	31.80	1.76E+04	6.28	46	31

Figure 5.4: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases during the time period 00:00 - 05:30.

The aftermath of the changes to the signaling intervals is visible also in Figure 5.4 as light cycle lengths for both intersections are fairly deflated.

Time period 05:31 - 08:00

In this time period, as can be seen in Figure 5.5, the minimal lengths for pedestrian crossing are sufficient and kept whereas all other phases are prolonged. Phase `"Left 1_2"` was increased up to 55 seconds to provide better results. Whereas phases `"Left 2_2"` and `"Right 1_2"` were caped at 40 seconds each.

	junction_left						*junction_right*			
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_1*	*Offset_right*
Default	33	5	32	5	6	0	37	5	42	0
2	12	55	9	40	6	0	9	40	15	0
1	12	40	9	35	6	0	9	40	15	0

Figure 5.5: Lengths of traffic light phases during the time period 05:31 - 08:00.

Peak-hour complication created by an incoming traffic flow into the fictional city center was estimated to need prolonging of both light cycles. Surprisingly this was disproved in Figure 5.6 which showcases distribution of light cycle lengths for specific intersections. While `junction_right` received a reduction in the overall light cycle length, `junction_right` is almost double of that amount.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	39.34	644.85	3.10E+05	5.49	90	90
2	29.72	536.12	2.18E+05	5.98	131	70
1	28.82	534.96	2.13E+05	5.99	111	70

Figure 5.6: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases during the time period 05:31 - 08:00.

The best configuration reduced the waiting time by **31.50%**, what corresponds to **97 743** seconds roughly converted into **27.15** hours. This value is already **42.90%** of whole reduction achieved by the pedestrian orientated model with invariant lengths of traffic light phases.

An important question to keep an eye on for the second appearance of the rush hour was: „Is one configuration of traffic node sufficient for all appearances of the rush hour complication or each requires its own plan?“. In a case where only one is plentiful, time needed for static variant optimization would be naturally lowered, henceforth would increase potential of this approach.

Time period 08:01 - 14:00

The next time period on the list was the one between the two rush hour complications. Even though traffic volume was relatively high, the best configuration, as seen in Figure 5.7, was the one with minimal possible allocation for all of the traffic light phases.

	junction_left						junction_right			
	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right
Default	33	5	32	5	6	0	37	5	42	0
2	12	5	9	5	6	0	9	5	8	0
1	12	5	9	5	6	0	9	5	8	17

Figure 5.7: Lengths of traffic light phases during the time period 08:01 - 14:00.

Pedestrian crossings were kept at their plausible minimum, in this case for both `junction_left` as well as `junction_right`. Other phases, that ensure emptying of the intersection, were also kept at their minimal value. Phases `"Left 3_1"` and `"Right 2_2"` had higher intervals for the intersection clearance, set at 6 and 8 seconds respectively. However, these were minimal values capable of providing improvements to the measured objectives. And for that very reason, these intervals could not be deflated any further and were considered minimal possible for these phases when referencing them.

The two best configurations were only inconsistent concerning an offset on the `junction_right`. The offset was set to simulate coordination between the two intersections. Although, reduction brought by an addition of the offset on the traffic node is negligible as reflected in Figure 5.8.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	19.37	211.13	1.82E+05	6.23	90	90
2	14.68	160.91	8.75E+04	7.13	46	28
1	14.62	160.10	8.61E+04	7.15	46	28

Figure 5.8: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases during the time period 08:01 - 14:00.

As can be seen in Figure 5.8, light cycle lengths for both intersections were notably reduced. The main objective was, through implementation of optimized TSMP for the time period 08:01 - 14:00, reduced by **52.77%**, that correlates with the total of **26.71** hours of unnecessary daily commute that was saved for drivers.

Time period 14:01 - 16:30

The second appearance of the rush hour was anticipated to follow the same configuration as the first one did. Nevertheless, the first one showed the best results when light cycle on `junction_left` was prolonged and so were its phases. Yet this time period required totally different approach, due to the fact that traffic is directed in an opposite manner than during morning rush hour. If the same TSMP was used for this time period as it was used previously, it would actually create increased rate of waiting time, rather than reduction.

As can be seen in Figure 5.9, the lengths for pedestrian crossings were once again generated at minimal possible rate to ensure safe passage. Alike, both light cycles were significantly deflated. This answers the question whether or not is it sufficient to use only one configuration for multiple rush hour complications in the development and implementation of complex TSMP. Each time period, even if traffic demand was mirrored with only difference of the cardinal-direction of main traffic flow, required its own TSMP. Hence, due to the fact that traffic node consists of mismatched intersections answer to the question is negative.

	junction_left						*junction_right*			
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_1*	*Offset_right*
Default	33	5	32	5	6	0	37	5	42	0
2	12	20	9	13	6	0	9	20	23	0
1	12	20	9	13	6	0	9	11	23	0

Figure 5.9: Lengths of traffic light phases during the time period 14:01 - 16:30.

As Figure 5.10 presents, distribution of light cycle lengths was more similar than in previous time periods, where length of light cycle on `junction_left` was often almost doubled compared to `junction_right`.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths	
					junction_left	junction_right
Default	46.08	620.90	2.96E+05	5.63	90	90
2	32.18	556.19	2.38E+05	5.96	69	58
1	32.12	553.21	2.36E+05	5.96	69	49

Figure 5.10: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases during the time period 14:01 - 16:30.

However, with the use of different lengths for the traffic light phases than in previous rush hour, the improvement is not as significant concerning the waiting time. The best configuration resulted in **20.27%** decrease of the measured objective.

Time period 16:31 - 23:59

The time period 16:31 - 23:59 was set to overload traffic node with not only vehicles, but in large amount also pedestrians, thus two separate approaches needed to be explored.

On the one side, configuration that was orientated towards pedestrians, with extended intervals for phases `"Left 1_1"`, `"Left 2_1"`, `"Right 1_1"` as well as phase `"Right 2_2"`. All of the mentioned phases were not extended in comparison with the default values gathered from SUMO, but rather in comparison with the second approach that favors distribution towards more balanced lengths of traffic light phases between pedestrians and vehicular transportation. The second approach keeps lengths of phases at their minimum. Both of these approaches to the traffic lights optimization during the time period 16:31 - 23:59 are displayed in Figure 5.11.

	junction_left						*junction_right*			
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_1*	*Offset_right*
Default	33	5	32	5	6	0	37	5	42	0
2	28	5	27	5	6	0	37	5	16	0
1	12	5	9	5	6	0	9	5	8	0

Figure 5.11: Lengths of traffic light phases during the time period 16:31 - 23:59.

Additionally, both showed similar measurements presented in Figure 5.12, but with very distinct light cycle lengths. From this conclusion can be drawn, that often times there are multiple very similarly resulting configurations, but with very distinct approaches to the problem.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]	
					junction_left	junction_right
Default	18.85	141.18	1.53E+05	6.51	90	90
2	15.07	111.25	8.44E+04	7.67	80	64
1	14.44	108.50	7.37E+04	7.34	46	28

Figure 5.12: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases during the time period 16:31 - 23:59.

Figure 5.12 showcases, that the waiting time for the time period 16:31 - 23:59 achieved the downturn of **51.95%** compared to the default configuration.

Implementation and analysis of variant lengths of traffic light phases

Once satisfying configurations were found for every time period, simulation of the whole day was assembled. This was done by the use of `WAUT` element explained in Chapter 3.

At first decision was made to omit all offsets. And by doing so determine impact, that following addition of offsets would bring. Visual representation of the assembled TSMP configuration mentioned in this paragraph is located inside the appendix section as Figure A.10. Assembled configuration from all time periods without offsets showed surprising results illustrated in Figure 5.13. With **34.31%** decrease in the waiting time provided the most significant reduction of the main measured objective just yet.

Another important aspect, that needed to be examined further, was impact of offsets on the overall waiting time. Even though multiple time periods showed the greatest reduction with configured offsets. It was estimated that these would throughout the multiple frames cause unprecedented behaviour to the main measured objective. The assembled TSMP configuration mentioned in this paragraph is displayed inside the appendix section as Figure A.11. The best resulting configuration for each time period was used, what as seen in Figure 5.13 resulted in **34.93%** reduction in the overall waiting time. Therefore by this approach, it was possible to introduce even bigger reduction than by any previous strategy. And also previous estimate of high impact of accumulated offsets was disproved.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]
Default	30.69	313.75	1.32E+06	5.57
3	24.53	251.31	8.67E+05	6.17
2	24.42	250.09	8.59E+05	6.17
1	23.08	236.35	7.99E+05	6.22

Figure 5.13: Comparison of the measured objectives between default TSMP and enhanced statically configured TSMP with variant lengths of traffic light phases.

Even though this result seemed satisfactory. Further calculations were in place to determine whether focusing on specific situation during time periods is beneficial. As mentioned previously time period 16:31 - 23:59 is unique in volume of pedestrians loaded into the simulation. Thus configuration that would extend lengths of the appropriate pedestrian phases was introduced. Visual representation of the assembled TSMP configuration mentioned in this paragraph is displayed inside the appendix section as Figure A.12. The second best configuration was used for this time period and results, also presented in Figure 5.13, showed astonishing rate of **39.43%** reduction in overall waiting time. This value correlates with **144.5** hours of saved unnecessary waiting time on daily basis.

5.3 Dynamic optimization

Even though results from static optimization shall be considered notable, especially those from variant static configurations. Dynamic optimization was estimated to produce results with even higher rate of reduction of the waiting time than any previous configuration. Then again, dynamic optimization comes with estimated implementation costs and implementation time frame far greater than static optimization does.

Traffic node presented in Chapter 3 required addition of monitoring devices in order to gather real time traffic conditions. Thus detectors were added onto the roads, as means for monitoring traffic situation during specific time periods. Corresponding traffic phases were elongated if queue of incoming vehicles was detected.

Default configuration

SUMO's default configuration for actuated traffic signal planning was by far more effective than static default configuration. Markedly, as shown in Figure 5.14, summed up to **1.05E+06** seconds of waiting time, what correlates with almost **293** hours of time loss for drivers on daily basis. Yet, this value corresponds to the **20.11%** decrease in the waiting time compared to the default static configuration, what is equivalent to **74** hours of the saved time on daily basis.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]			
					Minimal		Maximal	
					junction_left	junction_right	junction_left	junction_right
Default_S	30.69	313.75	1.32E+06	5.57	90	90	90	90
Default_A	27.00	273.06	1.05E+06	5.93	34	169	21	111

Figure 5.14: Comparison of main objectives between default static TSMP and default dynamic TSMP.

Enhanced dynamic configurations

Although when adjustments to the maximal duration of traffic light phases were applied coupled with addition of the offsets, further enhancements were reached. As illustrated in Figure 5.15 both configurations resulted in the reduced waiting time. It needs to be stated that results were reached under preconditions that all road users were assessed equally.

For configuration without set offsets between two intersections, the waiting time corresponded to **9.83E+05** seconds. Thus provided additional reduction equal to **74 377** seconds compared to default dynamic configuration generated by SUMO.

On the other hand, addition of the offsets produced slightly better reduction up to **9.80E+05** seconds of the summed up waiting time. This negligible improvement was produced mostly during the first time period of the simulation, but during other time periods addition of offsets was insignificant.

	travel time [sec]	density [veh/km]	waiting time [sec]	speed [m/s]	Cycle Lengths [sec]			
					Minimal		Maximal	
					junction_left	junction_right	junction_left	junction_right
Default_S	30.69	313.75	1.32E+06	5.57	90	90	90	90
Default_A	27.00	273.06	1.05E+06	5.93	34	169	21	111
3	25.87	262.95	9.83E+05	6.00	34	155	21	121
2	25.89	263.05	9.80E+05	6.00	34	155	21	121
1	22.01	224.63	7.48E+05	6.35	135	189	70	143

Figure 5.15: Comparison of main objectives between default TSMPs and enhanced dynamically configured TSMPs.

On the contrary when approach for maximized vehicular traffic was introduced rather than equal assessment, waiting times dropped rapidly. The main measured objective finalized at **7.48E+05** seconds throughout the day. This value, presented in Figure 5.15, corresponds to **43.31%** decrease of the waiting time or **158.76** hours of daily saved time for drivers compared to the default static configuration for the chosen traffic node.

5.4 Comparison of static optimization of TSMPs

Both static optimization techniques produced notable reduction in the waiting time. In order to determine differences between two approaches decision was made to focus on the three best configurations of each approach. These were compared to each other as well as to the default static configuration according to the extended measured objectives. The default static configuration is referred to as configuration number 1 inside all graphs in this section.

As seen in Figure 5.16, greater rate of reduction was achieved by static configuration with variant lengths of traffic light phases. That was true for each of the three configurations.

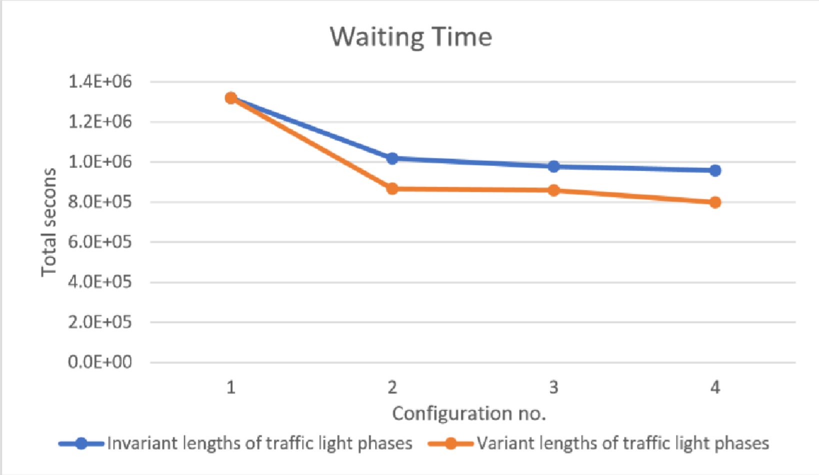
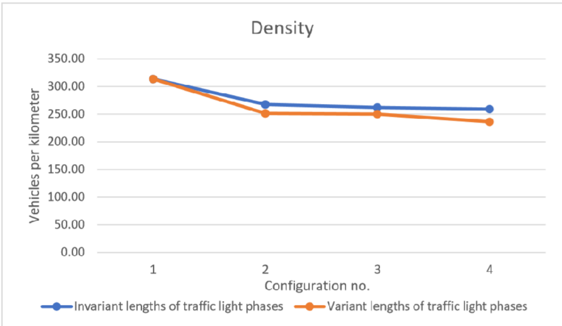


Figure 5.16: Comparison between two static optimization techniques concerning waiting time.

A similar trend was also reappearing in other measured objectives. As can be seen in Figures 5.17 and 5.18 rates of reduction achieved by the static configuration with variant lengths of traffic light phases were superior.



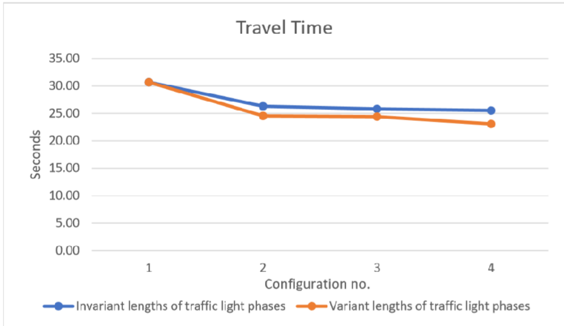


Figure 5.17: Comparison between two static optimization techniques concerning travel time and road density.

As illustrated in Figure 5.18, speed of vehicles rose more rapidly when updated static TSMPs with variant lengths of traffic light phases were used. Nonetheless, the highest enhancement of vehicular speed inside the simulation stagnated far beneath allowed maximal speed for the chosen traffic network.

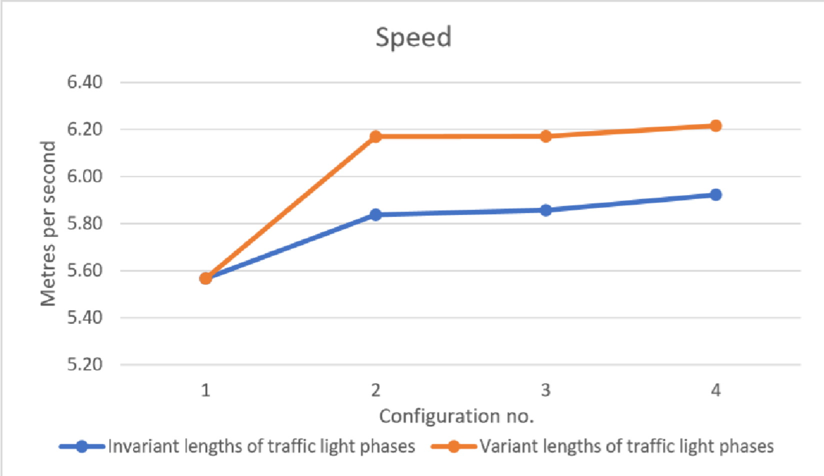


Figure 5.18: Comparison between two static optimization techniques concerning speed of vehicular traffic.

The static configuration of TSMP with variant lengths of traffic light phases was superior in all measured objectives. However, it is important to specify that reduction in travel time and density of the roads is quite minor. Hence, if reason for optimization of outdated TSMP is either high travel time or unmanageable road density, then difference between two techniques is insignificant. In that case, other factors such as implementation period or the financial costs should be considered first to determine which static optimization technique to apply.

On the other side of the spectrum, if the reasoning behind traffic signal light optimization is to decrease overall waiting time for specific traffic node, then static optimization technique with variant lengths of traffic light phases should be prioritised.

5.5 Comparison between static and dynamic optimization of TSMPs

Static TSMPs with variant traffic light phases provided greater improvements in all measured objectives than its static counterpart. Thus decision was made to compare the best configurations of dynamic TSMP to the three best configurations of superior static approach of TSMP optimization. Additionally, the default static configuration as well as the default dynamic configuration were included in the comparison. The default configurations are referred to as configuration number 1 inside all graphs for this section.

As can be seen in Figure 5.19, the greatest reduction of waiting time was achieved by the dynamic configuration of TSMP. Nevertheless, the best static configuration was not far away and provided just slightly worse results.

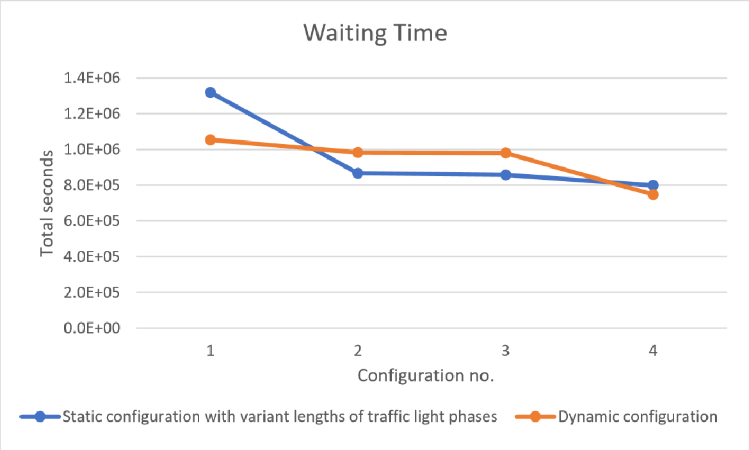


Figure 5.19: Comparison between static configuration of TSMP with variant lengths of traffic light phases and dynamic configuration of TSMP concerning waiting time.

Important to mention is the fact, that the waiting time measured for multiple static configurations resulted in greater reduction than dynamic configuration did.

Figure 5.20 showcases that dynamic configuration provided the best results not only for the measured waiting time, but also for the travel time. By updating the old traffic signal management plan not only was it possible to reduce unnecessary intervals drivers spend waiting, but also reduction of travel time was possible up to **28.28%** compared to its initial value.

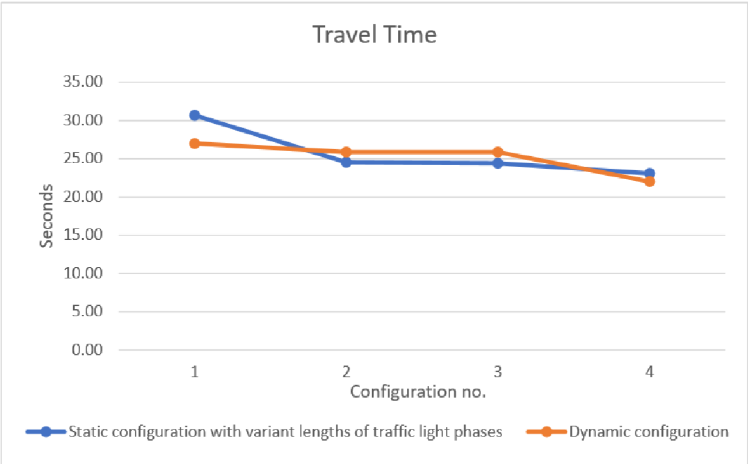


Figure 5.20: Comparison between static configuration of TSMP with variant lengths of traffic light phases and dynamic configuration of TSMP concerning travel time.
As a result of improved traffic signal management plans, roads are less likely to be overwhelmed by traffic volume. This is a result of more balanced allocation of green time for light phases, that helps to create smoother and more stabilized traffic. Tendency of decreasing density of the traffic node can be seen in Figure 5.21.

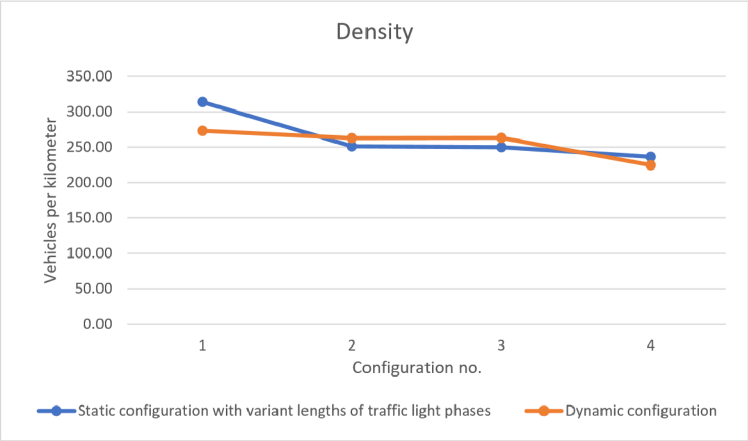


Figure 5.21: Comparison between static configuration of TSMP with variant lengths of traffic light phases and dynamic configuration of TSMP concerning density of the roads.

An average number of vehicles per kilometer, that were occupying the roads with the static default configuration reached **314** cars. With the improved dynamic configuration number of vehicles dropped to **225** vehicles, what represents notable downturn of **28.34%**.

Demand for roads far outstrips supply, thus even with reduction density of the roads, this would probably be just a temporary effect. Sooner than later, number of cars would once again start to rise. This phenomenon is not going to change until some techniques of driver's motivation to reduce traffic are implemented. These might include park-and-ride schemes or instrumenting of a toll on parking inside the city center.

With decrease in density of vehicular transport on the road it was also essential to explore additional statistics of average speed, that vehicles were able to reach during transport, as this also favors travel time to reach its minimum. Throughout the various improvements in configuration of intervals for the traffic light phases, speed has had an increasing tendency throughout whole optimization process. Once again the best dynamic configuration showed the highest rate of improvement of the measured objective. Increasing tendency of average vehicular speed is presented in Figure 5.22.

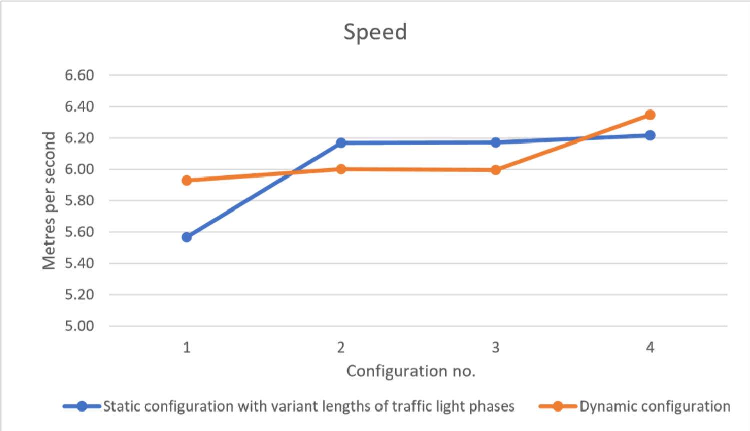


Figure 5.22: Comparison between static configuration of TSMP with variant lengths of traffic light phases and dynamic configuration of TSMP concerning average vehicle speed.

Nevertheless, the simulation showcased that improvement in overall speed was small, stagnated at **14%** of average increase, but more importantly caped at only **6.35** metres per second. The value is far below possible maximum speed of a traffic network, that was set to **15.278** metres per second. Value stagnated even when departure speed of incoming vehicles to the simulation was set to the maximal possible rate. Henceforth, the conclusion can be drawn, that the highest impact on the reduction of the waiting time reflects from enhanced traffic signal management plan directly at the intersection, rather than higher speed of vehicular flows.

Dynamic configuration showed the best reduction in all measured objectives. However, differences between the best-case scenarios for both static as well as dynamic configuration were negligible. Furthermore, multiple static configurations provided greater improvements than dynamic ones did. Of course with the exception of the best dynamic configuration. Thus it may not always be beneficial to seek restructuring of an intersection towards dynamic configuration, as this might have a worse effect when done suboptimally than a well carried out static optimization. For that reason a proper analysis of opportunity cost is recommended, when deciding between dynamic and static optimization of outdated TSMPs.

Updated traffic signal management plans not only enhanced the main measured objective of the waiting time, but also showed subsequent improvements to other important factors of traffic. Even though dynamic configuration was proved to provide the best outcomes as was initially expected, static variant configuration was not far behind when it came to the final results. To conclude, if opportunity costs are higher for a reconstruction of a dynamic traffic node, then static variant configuration of traffic signal management plan may be sufficient to achieve the desired outcome.

Chapter 6

Conclusion

In conclusion, repeated experimentation with the modeled traffic node proved importance of remodeling outdated traffic signal management plans. By introduction of various traffic scenarios as well as different road users it adequately resembled real world scenarios. Throughout the paper various approaches to the optimization of traffic lights management were analyzed and outlined.

Improved rates of the measured main objective are considered notable. Nonetheless, the heuristic approach does not provide the globally optimal solution, but it gives a good local solution as proven in the bachelor's thesis by reducing waiting time by a significant margin together with decreased travel time, increased average speed of vehicles and reduced traffic density on the chosen traffic node. All of the mentioned factors directly redound to the overall throughput of the intersection, but their impact on safety could be explored further to ensure applicability onto a greater scale.

In the future I would like to focus on more specific traffic scenarios such as emergency situations where whole node is halted for a significant time period. Special focus shall be set on exploring emergency protocols that need to be followed during that occurrence. Another approach for future expansion could include calculations of carbon footprint created inside urban areas, followed by an analysis of the reduced carbon impact brought by updated TSMPs.

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Appendix A

Overview of TSMP configurations and measured objectives

Static configurations of traffic light phases

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right	Waiting Time
Default	33	5	32	5	6	0	37	5	42	0	**1319646.16**
1	31	5	34	5	6	0	37	5	42	0	**1423100.97**
2	37	5	28	5	6	0	37	5	42	0	**1326078.69**
3	38	5	27	5	6	0	37	5	42	0	**1319651.15**
4	39	5	26	5	6	0	37	5	42	0	**1285091.02**
5	40	5	25	5	6	0	37	5	42	0	**1296405.16**
6	37	5	26	5	8	0	37	5	42	0	**1329281.94**
7	38	5	27	5	8	0	37	5	42	0	**1329923.75**
8	39	5	24	5	8	0	37	5	42	0	**1328286.77**
9	37	5	26	7	6	0	37	5	42	0	**1287663.99**
10	37	5	25	8	6	0	37	5	42	0	**1307929.31**
11	37	7	26	5	6	0	37	5	42	0	**1293902.99**
12	37	8	25	5	6	0	37	5	42	0	**1272299.98**
13	37	9	24	5	6	0	37	5	42	0	**1255973.26**
14	37	10	23	5	6	0	37	5	42	0	**1289630.65**
15	36	10	24	5	6	0	37	5	42	0	**1255170.38**
16	35	11	24	5	6	0	37	5	42	0	**1261269.09**
17	35	10	24	6	6	0	37	5	42	0	**1284516.75**
18	39	7	24	5	6	0	37	5	42	0	**1272896.28**
19	37	9	24	5	6	5	37	5	42	0	**1232116.9**
20	37	9	24	5	6	10	37	5	42	0	**1242219.4**
21	37	9	24	5	6	7	37	5	42	0	**1240793.88**
22 *	36	10	24	5	6	5	37	5	42	0	**1222698.26**
23	36	10	24	5	6	10	37	5	42	0	**1229215.78**
24	36	10	24	5	6	7	37	5	42	0	**1222988.24**
25	35	11	24	5	6	5	37	5	42	0	**1229603.09**
26	35	11	24	5	6	10	37	5	42	0	**1237448.49**
27	35	11	24	5	6	7	37	5	42	0	**1243027.64**

Figure A.1: Static invariant configurations with changes applied only on junction_left.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right	Waiting Time
Default	33	5	32	5	6	0	37	5	42	0	1319646.16
1	33	5	32	5	6	0	42	5	37	0	1297787.17
2	33	5	32	5	6	0	47	5	32	0	1259328.49
3	33	5	32	5	6	0	48	5	31	0	1274315
4	33	5	32	5	6	0	46	5	33	0	1261648
5	33	5	32	5	6	0	47	7	30	0	1296902
6	33	5	32	5	6	0	45	7	32	0	1245319
7	33	5	32	5	6	0	43	9	32	0	1337386.96
8	33	5	32	5	6	0	45	8	31	0	1315696.34
9	33	5	32	5	6	0	46	6	32	0	1251125
10	33	5	32	5	6	0	46	7	31	0	1303012
11	33	5	32	5	6	0	47	5	32	5	1178636
12	33	5	32	5	6	0	47	5	32	10	1185584
13	33	5	32	5	6	0	47	5	32	15	1177138
14 *	33	5	32	5	6	0	47	5	32	17	1133410
15	33	5	32	5	6	0	47	5	32	19	1140781
16	33	5	32	5	6	0	45	7	32	5	1313489.69
17	33	5	32	5	6	0	45	7	32	10	1214421
18 *	33	5	32	5	6	0	45	7	32	15	1134307
19	33	5	32	5	6	0	45	7	32	17	1136218
20	33	5	32	5	6	0	46	6	32	5	1203290.02
21	33	5	32	5	6	0	46	6	32	10	1172448
22	33	5	32	5	6	0	46	6	32	15	1146752
23	33	5	32	5	6	0	46	6	32	17	1142039
24 *	33	5	32	5	6	0	46	6	32	19	1136167.8
25	33	5	32	5	6	0	46	6	32	20	1139677.05

Figure A.2: Static invariant configurations with changes applied only on junction_right.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right	Waiting Time
Default	33	5	32	5	6	0	37	5	42	0	**1319646.16**
1	37	9	24	5	6	0	47	5	32	0	**1109561**
2	37	9	24	5	6	0	45	7	32	0	**1127480**
3	37	9	24	5	6	0	46	6	32	0	**1131332**
4	37	9	24	5	6	0	47	5	32	17	**1141060**
5	37	9	24	5	6	0	45	7	32	15	**1148477**
6	37	9	24	5	6	0	46	6	32	19	**1149838**
7	36	10	24	5	6	0	47	5	32	0	**1113030**
8	36	10	24	5	6	0	45	7	32	0	**1122983**
9	36	10	24	5	6	0	46	6	32	0	**1117427.17**
10	36	10	24	5	6	0	47	5	32	17	**1137885**
11	36	10	24	5	6	0	45	7	32	15	**1142740**
12	36	10	24	5	6	0	46	6	32	19	**1180936**
13	35	11	24	5	6	0	47	5	32	0	**1117684**
14	35	11	24	5	6	0	45	7	32	0	**1125623**
15	35	11	24	5	6	0	46	6	32	0	**1125188**
16	35	11	24	5	6	0	47	5	32	17	**1138734**
17	35	11	24	5	6	0	45	7	32	15	**1148227**
18	35	11	24	5	6	0	46	6	32	19	**1136652**
19	37	9	24	5	6	5	47	5	32	0	**1100726**
20	37	9	24	5	6	5	45	7	32	0	**1175304**
21 *	37	9	24	5	6	5	46	6	32	0	**1096347**
22	37	9	24	5	6	5	47	5	32	17	**1125453**
23	37	9	24	5	6	5	45	7	32	15	**1146565**
24	37	9	24	5	6	5	46	6	32	19	**1129481**
25	36	10	24	5	6	5	47	5	32	0	**1095724**
26	36	10	24	5	6	5	45	7	32	0	**1138641**
27 *	36	10	24	5	6	5	46	6	32	0	**1095670.18**
28	36	10	24	5	6	5	47	5	32	17	**1126577**
29	36	10	24	5	6	5	45	7	32	15	**1172574**
30	36	10	24	5	6	5	46	6	32	19	**1134553**
31 *	35	11	24	5	6	5	47	5	32	0	**1091830**
32	35	11	24	5	6	5	45	7	32	0	**1100337**
33	35	11	24	5	6	5	46	6	32	0	**1093717.13**
34	35	11	24	5	6	5	47	5	32	17	**1123137**
35	35	11	24	5	6	5	45	7	32	15	**1144803**
36	35	11	24	5	6	5	46	6	32	19	**1128229**

Figure A.3: Static invariant configurations with changes applied on both intersections.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right	Waiting Time
Default	33	5	32	5	6	0	37	5	42	0	1319646.16
1	12	27	9	27	6	0	9	38	37	0	1084266
2	12	28	9	26	6	0	9	38	37	0	1077190
3	12	30	9	24	6	0	9	38	37	0	1076136
4	12	28	9	24	8	0	9	38	37	0	1108577
5	14	28	9	24	6	0	9	38	37	0	1075079
6	12	28	9	26	6	0	9	40	35	0	1064423
7	12	28	9	26	6	0	9	42	33	0	1064615
8 *	12	28	9	26	6	0	11	42	31	0	1029698
9	12	28	9	26	6	0	13	42	29	0	1051654
10	12	30	9	24	6	0	9	40	35	0	1059380
11 *	12	30	9	24	6	0	11	42	31	0	1025982
12	14	28	9	24	6	0	9	40	35	0	1056297
13 *	14	28	9	24	6	0	11	42	31	0	1018639
14	14	28	9	24	6	0	11	42	31	15	1095412.08
15	14	28	9	24	6	0	11	42	31	5	1070238
16	14	28	9	24	6	5	11	42	31	0	1000740
17	14	28	9	24	6	10	11	42	31	0	996393.4
18	14	28	9	24	6	15	11	42	31	0	990577
19	14	28	9	24	6	17	11	42	31	0	994734
20 *	14	28	9	24	6	15	11	42	31	5	958411
21	14	28	9	24	6	15	11	42	31	7	975022
22	12	30	9	24	6	0	11	42	31	5	1058047
23	12	30	9	24	6	5	11	42	31	0	1002495
24	12	30	9	24	6	10	11	42	31	0	994330
25	12	30	9	24	6	15	11	42	31	0	995724.85
26	12	30	9	24	6	10	11	42	31	5	980846
27 *	12	30	9	24	6	10	11	42	31	7	977286
28	12	30	9	24	6	10	11	42	31	10	977715
29	12	28	9	26	6	0	11	42	31	5	1109081
30	12	28	9	26	6	5	11	42	31	0	999974
31	12	28	9	26	6	10	11	42	31	0	1000261
32	12	28	9	26	6	5	11	42	31	5	980184
33	12	28	9	26	6	10	11	42	31	10	991233

Figure A.4: Static invariant configurations with changes applied on both intersections with addition of offsets.

Time period 00:00 - 5:30													
	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_2	Offset_right	Waiting Time	Cycle Lengths	
												junction_left	junction_right
Def.	33	5	32	5	6	0	37	5	42	0	38425	90	90
1	12	5	9	5	6	0	12	5	10	0	18402	46	33
2	12	5	9	5	6	0	12	5	15	0	19294	46	38
3	12	5	9	5	6	0	12	5	8	0	17787	46	31
4	12	5	9	5	6	0	12	5	5	0	18310	46	28
5	14	5	9	5	6	0	12	5	8	0	17948	48	31
6	12	5	11	5	6	0	12	5	8	0	18318	48	31
7	12	5	9	5	8	0	12	5	8	0	19735	48	31
8	12	5	9	5	6	0	14	5	8	0	17921	46	33
9	12	10	9	10	8	0	12	10	8	0	19667	58	36
10	12	5	9	5	6	0	12	5	8	5	17631	46	31
11	12	5	9	5	6	0	12	5	8	10	17929	46	31
12	12	5	9	5	6	5	12	5	8	0	18168	46	31
13	12	5	9	5	6	5	14	5	8	0	18465	46	33
14	12	5	9	5	6	0	14	5	8	5	18168	46	33

Figure A.5: Static variant configurations with changes applied during the time period 00:00 - 5:30.

Time period 5:31- 8:00													
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_2*	*Offset_right*	**Waiting Time**	**Cycle Lengths**	
												junction_left	**junction_right**
Def.	33	5	32	5	6	0	37	5	42	0	**310267**	**90**	**90**
1	33	5	32	5	6	0	47	5	32	0	**369133**	**90**	**90**
2	12	13	9	14	6	0	9	13	14	0	**245425**	**63**	**42**
3	12	16	9	16	6	0	9	16	16	0	**235290**	**68**	**47**
4	12	16	9	16	16	0	9	16	16	0	**358546**	**78**	**47**
5	12	19	9	19	6	0	9	19	19	0	**240198**	**74**	**53**
6	12	21	9	21	6	0	9	21	21	0	**254642**	**78**	**57**
7	16	16	13	16	6	0	13	16	16	0	**247789**	**76**	**51**
8	20	16	17	16	6	0	17	16	16	0	**258001**	**84**	**55**
9	14	16	11	16	6	0	11	16	16	0	**249730**	**72**	**49**
10	12	16	9	16	6	0	9	16	16	5	**245484**	**68**	**47**
11	12	16	9	16	6	0	9	16	16	10	**244361**	**68**	**47**
12	12	16	9	16	6	0	9	16	16	15	**240292.42**	**68**	**47**
13	12	16	9	16	6	0	9	16	16	17	**238580**	**68**	**47**
14	12	16	9	16	6	5	9	16	16	0	**244919**	**68**	**47**
15	12	16	9	16	6	5	9	16	16	5	**244963**	**68**	**47**
16	12	19	9	19	6	0	9	19	19	5	**250310**	**74**	**53**
17	12	19	9	19	6	5	9	19	19	0	**242441**	**74**	**53**
18	16	16	13	16	6	5	13	16	16	0	**247090**	**76**	**51**
19	16	16	13	16	6	0	13	16	16	5	**260520**	**76**	**51**
20	12	45	9	40	6	0	9	40	15	0	**219725**	**121**	**70**
21	12	45	9	40	6	0	9	50	15	0	**218253**	**121**	**80**
22	12	55	9	40	6	0	9	40	15	0	**218197**	**131**	**70**
23	12	40	9	45	6	0	9	40	15	0	**287572**	**121**	**70**
24	12	40	9	35	6	0	9	40	15	0	**212525**	**111**	**70**
25	12	45	9	40	16	0	9	40	15	0	**275623**	**131**	**70**
26	12	45	9	40	6	0	9	40	20	0	**229315**	**121**	**75**
27	12	46	9	40	6	0	9	40	15	0	**219229**	**122**	**70**
28	12	44	9	40	6	0	9	40	15	0	**231466**	**120**	**70**
29	12	45	9	41	6	0	9	40	15	0	**221176**	**122**	**70**
30	12	45	9	43	6	0	9	40	15	0	**226933**	**124**	**70**
31	12	45	9	39	6	0	9	40	15	0	**227963**	**120**	**70**
32	12	45	9	40	6	0	9	41	15	0	**220552**	**121**	**71**
33	12	45	9	40	6	0	9	43	15	0	**223720**	**121**	**73**
34	12	45	9	40	6	0	9	39	15	0	**222381**	**121**	**69**
35	12	45	9	40	6	0	9	37	15	0	**219817**	**121**	**67**
36	12	45	9	40	6	0	9	35	15	0	**226763**	**121**	**65**
37	12	45	9	40	6	0	9	45	30	0	**271468**	**121**	**90**
38	12	45	9	40	6	0	9	75	20	0	**231459**	**121**	**110**
39	12	55	9	40	6	0	9	40	15	5	**218777**	**131**	**70**
40	12	55	9	40	6	5	9	40	15	0	**220752**	**131**	**70**
41	12	40	9	35	6	0	9	40	15	5	**215492**	**111**	**70**
42	12	40	9	35	6	5	9	40	15	0	**219133**	**111**	**70**

Figure A.6: Static variant configurations with changes applied during the time period 5:31 - 8:00.

Time period 8:31- 14:00												Cycle Lengths	
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_2*	*Offset_right*	Waiting Time	junction_left	junction_right
Def.	33	5	32	5	6	0	37	5	42	0	182221	90	90
1	38	5	32	5	6	0	37	5	42	0	182577	95	90
2	28	5	32	5	6	0	37	5	42	0	182577	85	90
3	33	5	37	5	6	0	37	5	42	0	175012	95	90
4	33	5	27	5	6	0	37	5	42	0	172336	85	90
5	33	5	32	5	11	0	37	5	42	0	191184	95	90
6	33	5	32	5	6	0	42	5	42	0	177789	90	95
7	33	5	32	5	6	0	32	5	42	0	178743	90	85
8	33	5	32	5	6	0	37	5	47	0	185305	90	95
9	33	5	32	5	6	0	37	5	37	0	169245	90	85
10	12	45	9	40	6	0	9	40	15	0	178122	121	70
11	12	13	9	14	6	0	9	13	14	0	108497	63	42
12	12	16	9	16	6	0	9	16	16	0	117686	68	47
13	12	11	9	11	6	0	9	11	11	0	101541	58	37
14	12	9	9	8	6	0	9	9	8	0	93118	53	32
15	12	5	9	5	6	0	9	5	8	0	87457	46	28
16	12	5	9	5	6	0	9	5	8	5	87401	46	28
17	12	5	9	5	6	0	9	5	8	10	86783	46	28
18	12	5	9	5	6	0	9	5	8	15	86507	46	28
19	12	5	9	5	6	0	9	5	8	20	86672	46	28
20	12	5	9	5	6	0	9	5	8	17	86063	46	28
21	12	5	9	5	6	5	9	5	8	0	86566	46	28
22	12	5	9	5	6	10	9	5	8	0	86522	46	28
23	12	5	9	5	6	0	9	5	8	0	86684	46	28
24	12	5	9	5	6	10	9	5	8	17	86455	46	28

Figure A.7: Static variant configurations with changes applied during the time period 8:01 - 14:00.

Time period 14:01 - 16:30												Cycle Lengths	
	Left 1_1	*Left 1_2*	*Left 2_1*	*Left 2_2*	*Left 3_1*	*Offset_left*	*Right 1_1*	*Right 1_2*	*Right 2_2*	*Offset_right*	Waiting Time	junction_left	junction_right
Def.	33	5	32	5	6	0	37	5	42	0	295762	90	90
1	12	5	9	5	6	0	9	5	8	0	301273	46	28
2	12	45	9	40	6	0	9	40	15	0	375167	121	70
3	12	20	9	20	6	0	9	20	23	0	250773	76	58
4	12	25	9	20	6	0	9	20	23	0	252647	81	58
5	12	15	9	20	6	0	9	20	23	0	261804	71	58
6	12	20	9	25	6	0	9	20	23	0	265842	81	58
7	12	20	9	15	6	0	9	20	23	0	241149	71	58
8	12	20	9	13	6	0	9	20	23	0	238196	69	58
9	12	20	9	11	6	0	9	20	23	0	240415	67	58
10	12	20	9	20	11	0	9	20	23	0	265519	81	58
11	12	20	9	20	6	0	9	25	23	0	255371	76	63
12	12	20	9	20	6	0	9	15	23	0	249321	76	53
13	12	20	9	20	6	0	9	13	23	0	247755	76	51
14	12	20	9	20	6	0	9	11	23	0	247089	76	49
15	12	20	9	20	6	0	9	9	23	0	251573	76	47
16	12	20	9	20	6	0	9	20	28	0	260624	76	63
17	12	20	9	20	6	0	9	20	18	0	251381	76	53
18	12	20	9	13	6	0	9	11	23	0	235808	69	49
19	12	20	9	13	6	0	9	11	23	5	237088	69	49
20	12	20	9	13	6	5	9	11	23	0	238064	69	49

Figure A.8: Static variant configurations with changes applied during the time period 14:01 - 16:30.

Time period 16:31 - 23:59													
	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_2	Offset_right	Waiting Time	Cycle Lengths	
												junction_left	junction_right
Def.	33	5	32	5	6	0	37	5	42	0	153265	90	90
1	38	5	32	5	6	0	37	5	42	0	153684	95	90
2	28	5	32	5	6	0	37	5	42	0	146272	85	90
3	33	5	37	5	6	0	37	5	42	0	154907	95	90
4	33	5	27	5	6	0	37	5	42	0	143797	85	90
5	33	5	32	5	11	0	37	5	42	0	159182	95	90
6	33	5	32	5	6	0	42	5	42	0	149191	90	95
7	33	5	32	5	6	0	32	5	42	0	149319	90	85
8	33	5	32	5	6	0	37	5	47	0	158066	90	95
9	33	5	32	5	6	0	37	5	37	0	142740	90	85
10	28	5	27	5	6	0	37	5	37	0	109992	80	85
11	25	5	27	5	6	0	37	5	37	0	132962	80	82
12	31	5	27	5	6	0	37	5	37	0	135839	80	88
13	28	5	24	5	6	0	37	5	37	0	130894	77	85
14	28	5	30	5	6	0	37	5	37	0	136310	83	85
15	28	5	27	5	6	0	37	5	34	0	106162	80	82
16	28	5	27	5	6	0	37	5	40	0	116075	80	88
17	28	5	27	5	6	0	37	5	31	0	101952	80	79
18	28	5	27	5	6	0	37	5	28	0	97638	80	76
19	28	5	27	5	6	0	37	5	25	0	95262	80	73
20	28	5	27	5	6	0	37	5	22	0	91538	80	70
21	28	5	27	5	6	0	37	5	19	0	89180	80	67
22	28	5	27	5	6	0	37	5	16	0	84398	80	64
23	28	5	27	5	6	0	37	5	13	0	84820	80	61
24	28	5	27	5	6	0	37	5	16	5	89208	80	64
25	28	5	27	5	6	5	37	5	16	0	96695	80	64
26	12	5	9	5	6	0	9	5	16	0	86491	46	36
27	12	5	9	5	6	0	9	5	8	0	73651	46	28
28	12	10	9	5	6	0	9	5	8	0	76810	51	28
29	12	5	9	10	6	0	9	5	8	0	78666	51	28
30	12	5	9	5	6	0	9	10	8	0	74979	46	33

Figure A.9: Static variant configurations with changes applied during the time period 16:31 - 23:59.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right
00:00 - 05:30										
	12	5	9	5	6	0	12	5	8	0
05:31 - 08:00										
	12	40	9	35	6	0	9	40	15	0
08:01 - 14:00										
	12	5	9	5	6	0	9	5	8	0
14:01 - 16:30										
	12	20	9	13	6	0	9	11	23	0
16:31 - 23:59										
	12	5	9	5	6	0	9	5	8	0

Figure A.10: Assembled TSMP configuration from static variant configurations without offsets.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right
00:00 - 05:30										
	12	5	9	5	6	0	12	5	8	5
05:31 - 08:00										
	12	40	9	35	6	0	9	40	15	0
08:01 - 14:00										
	12	5	9	5	6	0	9	5	8	17
14:01 - 16:30										
	12	20	9	13	6	0	9	11	23	0
16:31 - 23:59										
	12	5	9	5	6	0	9	5	8	0

Figure A.11: Assembled TSMP configuration from static variant configurations with offsets.

	Left 1_1	Left 1_2	Left 2_1	Left 2_2	Left 3_1	Offset_left	Right 1_1	Right 1_2	Right 2_1	Offset_right
00:00 - 05:30										
	12	5	9	5	6	0	12	5	8	0
05:31 - 08:00										
	12	40	9	35	6	0	9	40	15	0
08:01 - 14:00										
	12	5	9	5	6	0	9	5	8	0
14:01 - 16:30										
	12	20	9	13	6	0	9	11	23	0
16:31 - 23:59										
	28	5	27	5	6	0	37	5	16	0

Figure A.12: Assembled TSMP configuration from static variant configurations with prioritised pedestrian movements during the time period 16:31 - 23:59.

###	Left 1_1			Left 1_2	Left 2_1			Left 2_2	Left 3_1			Offset_L	Right 1_1			Right 1_2	Right 2_1			Offset_R	Waiting Time
	Min.	Mean	Max.		Min.	Mean	Max.		Min.	Mean	Max.		Min.	Mean	Max.		Min.	Mean	Max.		
Def.	5	33	50	5	5	32	50	5	5	6	50	0	5	37	50	5	5	42	50	0	1054314
1	5	33	45	5	5	32	45	5	5	6	45	0	5	37	45	5	5	42	45	0	1058191
2	5	33	50	5	5	32	50	5	5	6	30	0	5	37	50	5	5	42	50	0	1014148.9
3	5	33	50	5	5	32	50	5	5	6	25	0	5	37	50	5	5	42	50	0	1002124.83
4	5	33	50	5	5	32	50	5	5	6	20	0	5	37	50	5	5	42	50	0	1045787.9
5	5	33	50	5	5	32	50	5	5	6	24	0	5	37	50	5	5	42	50	0	1009031.83
6	5	33	50	5	5	32	50	5	5	6	26	0	5	37	50	5	5	42	50	0	994928.74
7	5	33	50	5	5	32	50	5	5	6	27	0	5	37	50	5	5	42	50	0	1049086
8	5	33	55	5	5	32	55	5	5	6	26	0	5	37	55	5	5	42	55	0	982557
9	5	33	60	5	5	32	60	5	5	6	26	0	5	37	60	5	5	42	60	0	1020991
10	5	33	55	5	5	32	45	5	5	6	26	0	5	37	55	5	5	42	45	0	990517
11	5	33	50	5	5	32	50	5	5	6	26	0	5	37	50	5	5	42	50	5,15	1006803
12	5	33	50	5	5	32	50	5	5	6	26	5	5	37	50	5	5	42	50	0	1007962
13 *	5	33	55	5	5	32	55	5	5	6	26	0	5	37	55	5	5	42	55	5,15	982917
14 *	5	33	55	5	5	32	55	5	5	6	26	5	5	37	55	5	5	42	55	0	979937
15	5	33	55	5	5	32	55	5	5	6	26	15	5	37	55	5	5	42	55	0	984212.07

Figure A.13: Dynamic configurations with changes applied with intention of equal road user time distribution.

###	Left 1_1	Left 1_2			Left 2_1	left 2_2			Left 3_1			Offset_L	Right 1_1	Right 1_2			Right 2_1			Offset_R	Waiting Time
		Min.	Mean	Max.		Min.	Mean	Max.	Min.	Mean	Max.			Min.	Mean	Max.	Min.	Mean	Max.		
1	12	5	27	50	9	5	27	50	5	6	50	0	9	5	37	50	5	38	50	0	**775685**
2 *	12	5	27	50	9	5	27	50	5	6	26	0	9	5	37	50	5	38	50	0	**748106**
3	12	5	27	50	9	5	27	50	5	6	20	0	9	5	37	50	5	38	50	0	**769372**
4	12	5	27	50	9	5	27	50	5	6	30	0	9	5	37	50	5	38	50	0	**799386**
5	13	5	26	50	9	5	27	50	5	6	26	0	9	5	37	50	5	38	50	0	**769535**
6	12	5	27	50	10	5	26	50	5	6	26	0	9	5	37	50	5	38	50	0	**792457**
7	12	5	27	50	9	5	27	50	5	6	26	0	10	5	36	50	5	38	50	0	**792665**
8	12	5	27	55	9	5	27	55	5	6	26	0	9	5	37	55	5	38	55	0	**770051**

Figure A.14: Dynamic configurations with changes applied with intention of prioritizing vehicular time distribution.

		travel time [s]	density [veh/km]	waiting time [s]	speed [m/s]
1	**static/default**	30.69	313.75	1319646.16	5.57
2	**static_invariant/1**	28.21	287.22	1133410.00	5.72
3	**static_invariant/2**	27.95	284.10	1096347.00	5.78
4	**static_invariant/3**	27.88	283.54	1095670.18	5.78
5	**static_invariant/4**	27.86	283.39	1091830.00	5.77
6	**static_invariant/5**	26.38	268.06	1029698.00	5.83
7	**static_invariant/6**	26.42	268.61	1025982.00	5.84
8	**static_invariant/7**	26.32	267.58	1018639.00	5.84
9	**static_invariant/8**	25.82	262.27	977286.00	5.86
10	**static_invariant/9**	25.54	259.19	958411.00	5.92
11	**static_variant/1**	24.53	251.31	866908.00	6.17
12	**static_variant/2**	24.42	250.09	858665.00	6.17
13	**static_variant/3**	23.08	236.35	799361.00	6.22
14	**actuated/default**	27.00	273.06	1054314.00	5.93
15	**actuated/1**	25.87	262.95	982917.00	6.00
16	**actuated/2**	25.89	263.05	979937.00	6.00
17	**actuated/3**	22.01	224.63	748106.00	6.35

Figure A.15: Overview of the measured objectives of all significant configurations used in Chapter 5.