Economical Optimization of Reversible Lane Systems

A study of modeling and optimizing the economic aspects of reversible lane systems in Gothenburg

Master's thesis in Infrastructure and Environmental Engineering

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Creating a Realistic and Optimized Model for Economic Evaluation of Reversible Lane Systems and Applying it to Central Gothenburg

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Creation, Application and Evaluation of an Optimization Model
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Abstract

Reversible lane systems are a strategy which aims to maximize the traffic flow by switching the direction of one, or several, lanes at a road segment. While the implementation of reversible lane systems has been studied in terms of optimizing the total travel time in a traffic system, the economic impacts has historically often been overlooked. In this report a mathematical model is developed that optimizes the economic output of implementing reversible lane systems. The suggested model is a bi-level optimization model. The upper level maximize the economic output through altering the lane configuration and the lower level minimize the total system travel time in accordance with the methodology for System Optimum. The model is evaluated through applying it on central Gothenburg, Sweden. Here a Genetic Algorithm, provided in MATLAB's Global Optimization Toolbox, is used to implement the model. Due to the restrictions imposed by this algorithm the bi-level programming model is implemented as two separate optimization problems. The two models are used iteratively where the output of the former is used as input in the latter, and vice versa, until an optimized lane configuration is generated. In the end it is concluded that it would not be profitable to implement reversible lane systems in Gothenburg with the current traffic level. Moreover, it is concluded that while the model can be used to generate an indication of the potential profitability of reversible lane systems more developments are needed before basing large infrastructural investments on results generated by this model.

Keywords: reversible, lane, system, economical, optimization.

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Johannes Sundeen, Gothenburg, May 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

FFTT	Free Flow Travel Time
GA	Genetic Algorithm
HB	Histogram based
LPF	Link Performance Function
NDP	Network Design problem
OD-matrix	Origin Destination Matrix
OD-pair	Origin Destination Pair
RLS	Reversible Lane System
SI	Signalized Intersection
SO	System Optimization
UE	User Equilibrium

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

a	Index for a link in a traffic network
i, j	Indices for row and coulomb placement in matrices
k	Index for different paths between a OD-pair
n	Index for a node in a traffic network
w	Index for a OD-pair in a traffic network

Sets

$\mathcal{A}$	Set of potential links in a Traffic network
$\mathcal{A}$'	Sets of existing links in a Traffic network
$\mathcal{N}$	Set of nodes in a Traffic network
$\mathcal{Q}$	Set of Travel demand between OD-pairs in a Traffic network
$\mathcal{U}$	Set of Lane configuration variables
$\mathcal{W}$	Set of OD-pairs in a Traffic network

Parameters

α	Coefficient for link performance function
α_1	Initial Coefficient for link performance function
β	Coefficient for link performance function
β_1	Initial Coefficient for link performance function
δ	Coefficient for denoting if a link a is used in any path f_k^w

θ	Coefficient for the assumed level of knowledge travelers has of their traffic system
b	Coefficient for link performance function
l	The total number of existing links in a traffic network
m	The number of viable paths between each OD-pair in the traffic network
n	The number of nodes in the traffic network
r	Coefficient for converting velocities from [miles/hour] to [km/h]

Variables

$ADTV$	Average Daily Traffic Volume
BC	Base capacity for a highway
C	Total road traffic capacity
C_0	Initial total road traffic capacity
c	Traffic capacity for one lane
d	Yearly number of working weeks the system is active
ET	Passenger car equivalent for a highway
FFS	The Free flow travel speed on a link
f_{hv}	Adjustment factor for heavy vehicles on a highway
f_k^w	Traffic flow on path k between OD-pair w
g	Economic value of saved travel time [kr/h]
g_t	Effective green time in a signalized intersection [sec]
HV_c	Calculated adjustment factor for heavy vehicles on a freeway
HV_m	Collected adjustment factor for heavy vehicles on a freeway
l	Length of a link [m]
N	Number of lanes on link a link
p_0	Investment cost of purchasing a Zipper machine [kr/veh]
p_1	Investment cost of implementing RLSs [kr/m]
p_2	Daily operational cost for barriers using RLSs [kr/(m*day)]
p_3	Daily operational cost for zipper machine using RLSs [kr/(day)]
P_d	Peak hour direction proportion
PHT	Peak hour traffic volume
PT	Proportion of heavy vehicles on a highway
p_z	Proportion of time a zipper machine is used transfers barriers

q_w	Travel demand between an OD-pair w
S	The economic output for a lane configuration
S_t	Average deviation from the initial travel time t_1
S_{tt}	Average deviation from the initial total travel time TT_0
t_0	Free flow travel time
t_1	Travel time on a link calculated with the initial LPF parameters α_1 & β_1
t	Average travel time on a link
T_c	Total cycle length in an intersection [sec]
TT	Total travel time for a traffic system [min]
TT_0	Initial total travel time for a traffic system [min]
u_a	Lane configuration variable
v_0	Speed limit
v_z	Traveling speed of zipper machine [km/h]
x	Traffic flows on a link
y	Number of years
z	Notation for the feasibility of implementing a RLS on a link

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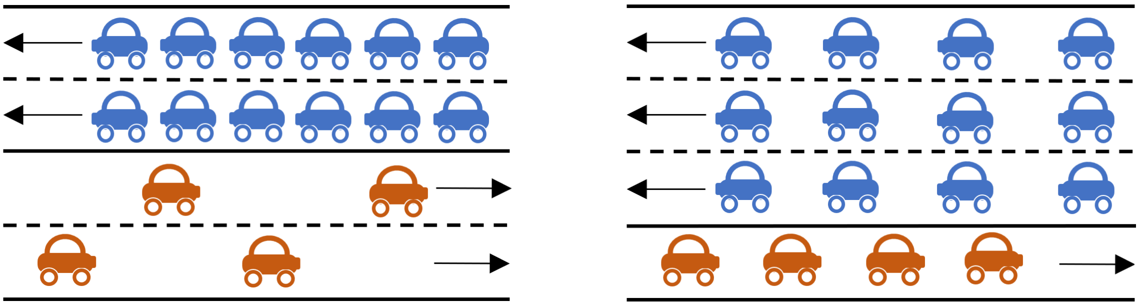
Introduction

1.1 Background

Traffic congestion is a state which occurs when a road is exposed to a higher traffic volume than the road capacity (Tang & Hu, 2019). It is a substantial issue within the modern world. For example, the average American spending about 100 hours stuck in traffic annually (INRIX, 2019). On an individual level, traffic congestion negatively impacts the citizens quality of life (Weisbrod et al., 2003). Additionally, the wasted time and the delivery delays that congestion creates also limits the economic growth on both a local and national level. Furthermore, by being stuck in traffic vehicles also generate more emissions than if they were to travel only in free-flowing traffic (Barth & Boriboonsomsin, 2008).

While congestion is a widespread problem it is most prevalent in and around larger urban areas which are exposed to higher traffic volumes (Liu & Wu, 2017). As the urban population is expected to grow worldwide during the upcoming decades (UN, 2018) this already problematic traffic situation could become even more severe in the near future. With this prediction in mind, it is of the utmost importance to find solutions to relive urban areas of traffic congestion. Since congestion is a consequence of insufficient capacity in relation to a traffic volume the solutions need provide a method to either reduce the traffic volume or increase the capacity. Instinctively, the solution to the problem is to simply increase the capacity of traffic systems by construction of new roads or expansion of the roads already in place. Though apart from being very costly, it also often not possible in urban areas where the available space is limited by buildings and other constructions (Meng et al., 2008).

A solution that can increase the capacity of a road or network while working within spatial restrictions posed by an urban area is Reversible Lane Systems (RLSs). With a RLS, one or several lanes on a road do not have a fixed direction (Meng et al., 2008). Instead, the direction of the reversible lanes can be changed to allow traffic to travel in the opposite direction, should the necessity arise. This means that while the total space available for traffic do not increase it can result in the space being used more effectively, *figure 1.1a & 1.1b*. Naturally an uneven travel demand, for the two directions of the road, is required for this to be the case.



(a) *Before lane reversal.* **(b)** *After lane reversal.*

Figure 1.1: *Lane configuration on a three lane road before and after lane reversal.*

The concept of reversible lanes is by no means a new one. In fact, the first recorded instance of a reversible lane dates back almost 100 years (Wolshon & Lambert, 2006). However, throughout most of this period RLSs have mostly been used as temporary solutions to cope with predictable abnormal traffic demands due to sporting events, festivals and concerts (Zhao et al., 2014). During the 1990s RLSs also began seeing use as a method to increase the efficiency of evacuation from disaster areas (Mo et al., 2019). One instance of this was when Hurricane Floyd struck Mississippi, US, in 1999. During the past few decades, the use of RLSs as permanent installations has increased as well, particularly on key passages within larger metropolitan areas (Zhao et al., 2014).

Naturally, one reason for this is the fact that the traffic demand is higher in population dense areas (Liang et al., 2011). However, the large traffic demand is only one component of why this methodology is being implemented in urban areas. The other reason is that RLSs are particularly effective in places where the peak traffic is unevenly distributed between the two directions of a road. In many larger metropolitan areas this occurs daily since they are exposed to large volume of commuters (Liang et al., 2011). Since the commuters generally live outside the urban centre but work centrally the travel demand is much larger towards the city than from it during the morning peak. Naturally, the reverse is true during the evening peak. This phenomenon is known as tidal effects.

Historically, there has not been a pre-set methodology on how or where RLSs should be implemented in order to maximize the congestion reduction (Meng et al., 2008). Instead, the characteristics and location of the RLSs has been determined by a combination of engineering judgement as well as trial and error testing. As a result of the lack of standardization, the methods currently adopted to construct a RLS vary greatly in terms of characteristics, scope and results (Wolshon & Lambert, 2006). A common solution is the use of a portable barrier in the middle lane which, when necessary, is moved by a zipper machine. This is currently used at the Golden Gate Bridge in San Francisco (Golden Gate Bridge, Highway and Transportation District, n.d.). Another solution, which is currently used in Beijing, China, is to display the direction on traffic lights suspended above the road (Ximeng, 2013). A more permanent solution can be found on the newly constructed I-5 express lanes towards Seattle, USA where the express lanes are open in the direction toward the city until 11 am and open from the city between 11.15 am-11 pm (Washington State Department of Transportation, n.d.).

Even though many of the RLSs currently in practice were conceived through primitive methods, such as trial and error tactics, evaluation of these systems has shown that they, generally, are effective in reducing traffic congestion (Wolshon & Lambert, 2006). However, in later years more research has been conducted with the ambition to make the implementation of RLSs more systematic. In terms of these more systematic approaches the aim is that a the RLSs would become more optimal both in terms of placement and day-to-day operation (Meng et al., 2008). Making the implementation of RLSs more systematic might also aid in reducing the negative impact which RLSs, in general, has on traffic safety (Conceição et al., 2020). Though despite the rise of research and methods for a more systematic implementation of RLSs no method currently implements the economic costs for constructing and operating an RLS. With such an optimization model the optimal implementation in terms of the economical investment could be investigated in a systematic fashion.

1.2 Aim

The aim of this report is to create a systematic methodology to evaluate an optimal investment strategy for reducing traffic congestion in a traffic network by utilizing RLSs. For this the proposed methodology should evaluate if implementing RLSs is profitable or not. Furthermore, the model should identify where RLSs should be implemented for the cases where it is profitable. Finally, the study also aims to assess the effectiveness of the suggested method by means of using the method in a case study.

1.3 Problem description

In order to evaluate whether or not implementation of RLSs would be profitable for a traffic system a number of problems has to be evaluated. To asses the economic consequences for implementing RLSs both the cost for implementation and the economic benefits of running a RLSs are naturally fundamental. Of course, the economic benefits for this is entirely dependent on how much the RLSs reduces the congestion in the traffic system.

Thus, the congestion for different lane configurations has to be evaluated as well. Evaluating the congestion for different lane configurations are a very complex task as the traffic conditions can vary greatly between different lane configurations. This complexity is mainly due to the difficulty of generating realistic traffic conditions. Here some of the problematic issues are to define network and generating realistic movement within it. To illustrate these problems, imagine a traffic system with six intersections and seven roads, in this case called *Traffic network 1*, *figure 1.2*

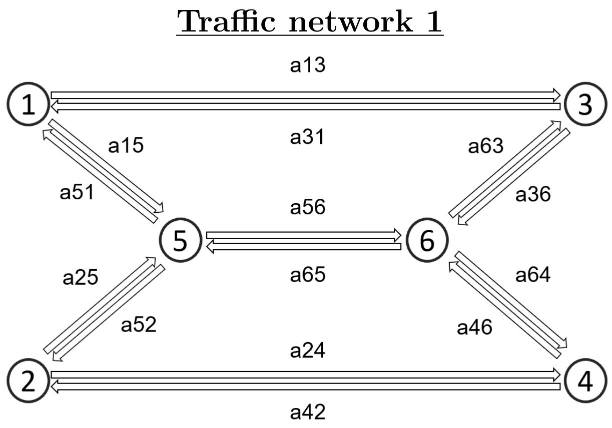


Figure 1.2: *Example of network notation in a simple traffic network including nodes and links.*

To successfully generate a realistic traffic condition, basic travel conditions have to be set. These include where traffic is generated, how large the generated traffic volumes are and to where the traffic intents to travel. As seen in *Traffic network 1*, there are several alternatives when traveling between any starting and end point within the traffic system. When traveling between intersection *1* and *3* a path using road 13 or 15, 56, 63 are both options which fulfils the requirement of connecting intersections *1* and *3*. This is usually the case for any traffic system. Thus, the distribution of the travellers that uses the different paths has to be evaluated as well. In this case it might seem obvious that all travelers would simply use the link which directly connects their origin and destination. However, there are more factors than distance which need to be taken into consideration. For example, if link *13* is heavily congested it might be quicker to travel through a longer route which is likely to effect travel behaviour between these two links. Thus, the traffic volume on the roads, the congestion and how that effect the travel behaviour has to be evaluated. With all this information set it is possible to simulate the effects posed by the change in lane configurations.

Successfully acquiring realistic answers to these questions requires some background knowledge within traffic engineering. The essential theory of which is presented in *Chapter 2: Theory*.

1.4 Limitations

There are many different approaches to reducing the congestion in cities but this report is solely concerned with the implementation of RLSs. As such the report do not investigate other methods for reducing congestion such as traffic reducing measures or construction of new links or lanes to the traffic network. While the potential to implement RLSs can be limited due to potential traffic safety issues this is not taken into consideration in this study. Furthermore, complications and limitations for implanting and operating a RLS in colder climates, with the presence of snow and ice is not accounted for. Additionally, the study does not take potential problems for implementing RLSs in close proximity to intersections or roundabouts. Naturally the efficiency of theses might be negatively impacted as a result of increasing the capacity for one direction of a road.

The scope of this study is limited in terms of both time and funding. As such the evaluation is performed by a single case study rather than several which would allow for a more in-depth evaluation of the suggested methodology. Furthermore, the time constraints posed on this study limits the amount of data which is feasible to collect. Thus, the evaluation is limited to information publicly available for the area of the case study. While there are extensive public records regarding many of the necessary data some vital information is either not publicly available or does not exist. Due to the limited timeframe the unavailable data has been assumed through reasonable calculations. Though alterations to a local traffic network could impact the travel behaviour within the entire city only the the links exposed to large travel flows are taken into account.

1.5 The study area

The case study investigates the profitability of RLSs in the city of Gothenburg, Sweden. Located centrally between the capitals of Sweden, Norway and Denmark, *figure 1.3*, Gothenburg is an important trading hub which is home to the largest port in Scandinavia (Port of Gothenburg, n.d.). With approximately 580.000 people living in the municipality of Gothenburg and a total of 1.000.000 inhabitants in the Gothenburg metropolitan area it is the second largest city in Sweden and the largest non-capital city in the Nordic countries (University of Gothenburg, 2022).

Figure 1.3: *Gothenburgs position in Scandinavia, background map provided by AutoNavi (AutoNavi Software Co., Ltd., n.d.).*

As with most cities the traffic system of Gothenburg is exposed to several challenges. A most critical challenge for Gothenburg is the river Göta älv which divides the city in two, the main land and the island Hisingen. When traveling between the two sides of Göta älv travellers are limited to the four passages between the sides, the bridges Älvsborgsbron & Hisingsbron and the tunnels Tingstadstunneln & Marieholmstunneln, *figure 1.4*. Apart from these passages the most important roads in Gothenburg are the highways scattered around the city. These highways are either European route highways, beltways (for connections within the city) or national roads connecting Gothenburg to the Landvetter airport and nearby cities such as Borås and Kungsbacka. An important aspect, apart from the roads themselves, of the Gothenburg traffic system is that trams are frequently utilized as a mode of public transport within the city centre. As trams are fixed in their choice implementing RLSs on roads where trams are present are not possible.

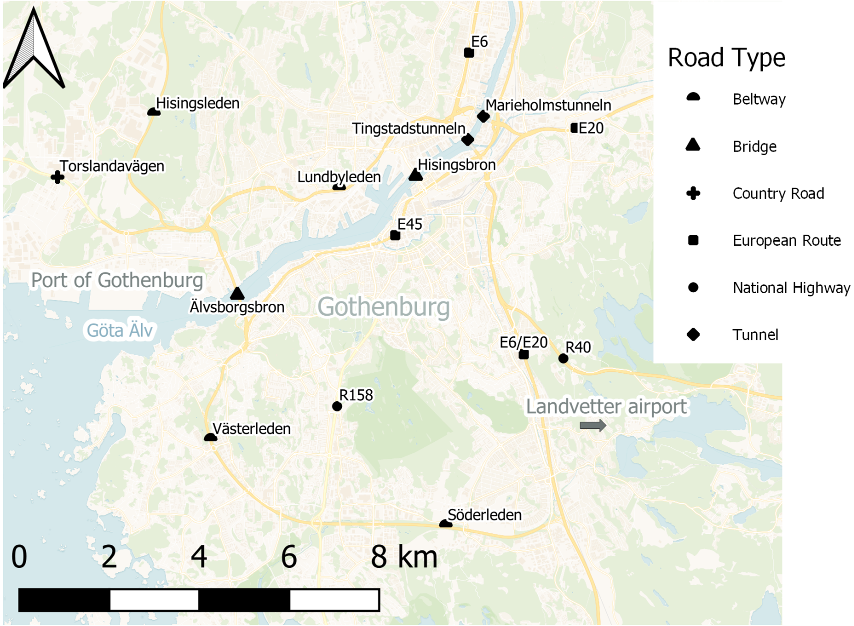


Figure 1.4: *The major highways in central Gothenburg, background map provided by Carto (CARTO, 2022).*

Due to the large population, and the city's function as a trading hub, Gothenburg is subjected to large traffic flows. During 2013 around 480.000 trips were performed on average with personal car every day and 23.000 trips with trucks (Göteborgs Stad, 2013). The maps used in this section, and throughout the rest of the report, have been created with the program *Qgis* (Qgis, 2022). The background map for all maps throughout the rest of this report were provided by CARTO (CARTO, 2022).

2

Theory

In the theory chapter the essential theoretical background upon which this report is crafted is presented. The theory chapter is divided into four sections. In section 2.1 the essential in traffic network definition is covered. Section 2.2 provides basic knowledge in traffic assignment theory. In section 2.3 the definition of a Network Design Problem is presented. Finally, in section 2.4 the fundamentals for programming models and solution algorithms are provided.

2.1 Defining a traffic network

In traffic engineering the relationship between a traffic system, characterised by roads and intersections, and the vehicles which interact with this system is studied. For the purpose of analysis and evaluation, traffic systems can be expressed in mathematical terms through the use of *graph theory* (Rodrigue & Ducruet, 2020). In graph theory real life systems are expressed through a network composed of nodes and links (Wilson, 1972). Nodes are the objects in the system and links are the mathematical expression of the connection between two nodes. By using this methodology, a traffic system is defined as a traffic network. In a traffic network the nodes can be used as a representation of intersections or parking lots while the links are the representation of the roads that connect them. Mathematically the set of nodes is expressed as a vector N which contains every node n_i, $n_i \in N$.

$$N = \begin{bmatrix} n_1 & n_2 & \cdots & n_{i-1} & n_i \end{bmatrix}'$$

This only denotes the nodes that exist in the traffic network but does not include any information regarding the relationships between them. Without any additional information the set of nodes are practically useless. However, when combined with a set of links the network can be described through graph theory. For a traffic network the links is expressed through a set, A, which contains every potential link a_{ij}, $a_{ij} \in A$. Here i denotes the stating node of the link and j denotes the end node of the link. To most accurately describe a network A is expressed as a matrix containing all positions of a_{ij}:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & \cdots & \cdots & a_{ij} \end{bmatrix}$$

Where the value of any a_{ij} is given the value of:

$$\begin{cases} 1 & \text{If a link between node } i \text{ and node } j \text{ exists} \\ 0 & \text{Otherwise} \end{cases}$$

As the links is a representation of the roads traveling between different nodes any link starting and ending at the same node, such as a_{11}, a_{22}, are defined as 0. From this set a subset, A', can be derived which only include the links which do exist.

On this point it is important to clarify that there are two types of graphs within graph theory; *undirected graphs*, where the links connect nodes symmetrically in both directions, and *directed graphs*, where the links connect nodes in a specified direction. For traffic application directed graphs are used. As a consequence of this roads with two directions, which includes most roads, are denoted through two separate links a_{ij} and a_{ji}.

As the reason for vehicles interacting with a traffic system is to move between two points vehicles has to be both introduced to and removed from the traffic network. This is achieved through the idea of origins and destinations. As the names imply, the origins are defined as points in the traffic network from which traffic is generated while destinations are points in the traffic network to which vehicles travel (F. L. Mannering & Washburn, 2013). Usually, a point is both an origin and a destination. Using this method allow for great flexibility as the location and number of origins or destinations can be changed for different purposes by the traffic engineer. Naturally, the accuracy of the model is expected to increase with the number of origin and destination points. However, this method for modelling a traffic system us not a completely accurate depiction of reality. Obviously real-life traffic is much more complicated as traffic can be generated anywhere and not just from a limited set of points. Despite this, using origins and destinations allow for a simplified version of reality for traffic analysis.

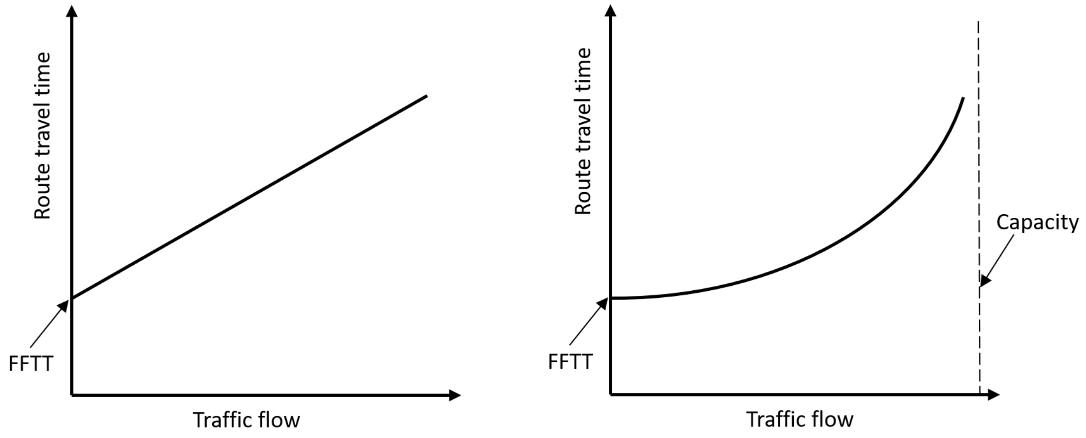
For a network the pairs of origins and destinations (OD-pairs) is described through a set of elements, W, $w_{ij} \in W$. Similarly, to link matrix, A, each element that denotes starting and arriving at the same node is set to 0. Additionally, the travel demand, q_{ij}, is defined though an Origin-Destination-matrix (OD-matrix), Q. As with the set of links and OD-pairs, the OD-demand for starting and arriving at the same node is set to 0. However, unlike the set of links, A, and OD-pairs, W, the values of the elements in the OD-matrix are not limited to ones and zeroes. Instead, they are simply defined as the number of vehicles that travel between the OD-pairs.

$$
W = \begin{bmatrix} 0 & w_{12} & \cdots & w_{1j} \\ w_{21} & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ w_{i1} & \cdots & \cdots & 0 \end{bmatrix} \qquad Q = \begin{bmatrix} 0 & q_{12} & \cdots & q_{1j} \\ q_{21} & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ q_{i1} & \cdots & \cdots & 0 \end{bmatrix}
$$

2.2 Traffic assignment

In a traffic network there are, usually, several viable options regarding which path a user chooses when traveling between an OD-pair. Commonly known as a traffic assignment problem, this creates a complex situation where the traffic engineers are tasked with determining the route choices made by the drivers.

There are many factors as to why a user might prefer one route over the others such as travel time, fuel cost and even less monitorable values such as scenery. However, usually travel time are used as the primary motivator for the decisions made by the drivers (F. L. Mannering & Washburn, 2013). Thus, the traffic assignment models are constructed as to assign traffic based on the travel time for the different paths. Given that the travel time for any path is dependent on the travel time on the links used in that path, the travel time for each individual link has to be expressed mathematically. Usually, this is achieved through the use of a *Link Performance Function* (LPF). For any link, a, the LPF expresses the relationship between the average travel and traffic flow on the link (F. L. Mannering & Washburn, 2013). A LPF includes at least two terms. Firstly, a constant which represents the travel time when no other vehicles use the link, known as the *Free Flow Travel time* (FFTT). Secondly, a term which emulates how the travel time increases with an increasing traffic flow. This relationship can be expressed either as linear or non-linear, *figure 2.1a & 2.1b.* As the traffic flow increases for a link with a non-linear expression the route travel time will increase exponentially. As a result, the travel time will enter a state where a small increase in traffic greatly affects the resulting travel time. This occurs when the traffic flow on the link is close to the capacity of the road. Here increasing the traffic flow further will cause heavy congestion.



(a) *Linear relationship.* **(b)** *Non-linear relationship.*

Figure 2.1: *Travel time-traffic flow relationship in for a linear and non-linear LPF (F. L. Mannering & Washburn, 2013).*

For a linear relationship the LPF is simply formulated as:

$$t_a(x_a) = t_0 + b * x_a \tag{2.1}$$

Where:

b: Constant to accurately represent the rate of increasing travel time

t_0: The FFTT

$t_a(x_a)$: The average travel time for a vehicle on link a dependent on x_a

x_a: The traffic flow on a link, a

Though LPFs are more commonly expressed as a non-linear relationships which more accurately reflects the real-life dynamics of travel time-traffic flow relationships. For this LPFs are usually constructed in accordance with the model for LPFs developed by *The U.S. Bureau of Public Roads*, (F. L. Mannering & Washburn, 2013). Such a LPF takes the form of:

$$t_a(x_a) = t_0 + \alpha * t_0(\frac{x_a}{C})^\beta \tag{2.2}$$

Where:

α: Constant to accurately represent the rate of increasing travel time

β: Constant to accurately represent the rate of increasing travel time

C: The total traffic flow capacity of the link

When using this formula, the values of α and β can be assigned in accordance with the standard values provided by *The U.S. Bureau of Public Roads* (F. Mannering et al., 1990), *table* 2.1.

Table 2.1: *Standard values of α and β for The U.S. Bureau of Public Roads LPFs (F. Mannering et al., 1990).*

Route speed limit [km/h]	Route capacity, C [veh/km]	Performance function parameters	
		α	β
$\leq$ 50	$\leq$ 250	0.7312	3.6596
$\leq$ 50	251-499	0.6128	3.5038
$\leq$ 50	500-749	0.8774	4.4613
$\leq$ 50	750-999	0.6846	5.1644
$\leq$ 50	$\geq$ 1000	1.1465	4.4239
51-65	$\leq$ 499	0.6190	3.6544
51-65	500-749	0.6662	4.9432
51-65	750-999	0.6222	5.1409
51-65	$\geq$ 1000	1.0300	5.5226
66-80	500-750	0.6609	5.0906
66-80	750-999	0.5423	5.7894
66-80	$\geq$ 1000	1.0091	6.5856
>80	$\leq$ 750	0.8776	4.9287
>80	750-999	0.7699	5.3443
>80	$\geq$ 1000	1.1491	6.8677

With the use of the travel time-traffic flow expressions traffic assignment methods become viable. While there are many different models for traffic assignment the most common are based on Wardrop's two approaches, System Optimization (SO) or User Equilibrium (UE) (F. L. Mannering & Washburn, 2013). As the name suggests SO is a representation of an ideal scenario where each individual chooses their travel path so that the total travel time for all individuals is as low as possible. Mathematically this is expressed as:

$$min\, TT(x_a) = \sum_a x_a t_a(x_a) \tag{2.3}$$

where:

a: A denotation for the links in the network $a \in A$

TT: The total travel time for all vehicles in the traffic network

The formula is also subjected to three constraints where the first denotes that the flow on all links is larger than zero. The second constraint defines that the sum of the traffic flow on all paths between an OD-pair adds up to the total traffic demand between that OD-pair. Lastly, the third constraint ensures that the traffic flow on each link is equal to the sum of traffic flow on all paths between all OD-pairs which passes through that link. Mathematically these constraints are formulated as:

$$\begin{cases} x_a \geq 0 & \forall\, a \in A \\ q_w = \sum_k f_k^w & \forall\, w \in W \\ x_a = \sum_w \sum_k f_k^w \delta_{a,k}^w & \forall\, a \in A,\, \forall\, w \in W \end{cases}$$

Where:

f_k^w: The traffic flow on a path k between and OD-pair w

k: Denotation for the available paths between an OD-pair

q_w: The total traffic demand for a OD pair w

w: Denotation for the OD-pairs $w \in W$

$\delta_{a,k}^w$ = The set of related factors which denotes if link a is used in path k for the OD-pair w. The value of $\delta_{a,k}^w$ is set as:

$$\delta_{a,k}^w = \begin{cases} 1 & \text{if link } a \text{ is used in path } k \text{ between OD-pair } w \\ 0 & \text{Otherwise} \end{cases}$$

SO is a convenient formulation to simulate driver behaviour, and an optimal outcome for traffic planners to strive towards. However, it rests on the assumption that users accept higher travel times for them as long as it is beneficial for the total travel time of all users. Naturally, this assumption does not reflect the behaviour of drivers in a real life-scenario. In reality, individuals are most likely to choose a travel path as to minimize their individual travel time, regardless of the consequences for total system travel time. Luckily, the traffic distribution under such traveller behaviour can be assigned with the use of a UE formula. Mathematically this is expressed as:

$$min\; TT(x_a) = \sum_a \int_0^{x_a} t_a(x_a) dx_a \tag{2.4}$$

Similarly to equation 2.3, the UE formulation are subjected to three constraints:

$$\begin{cases} x_a \geq 0, & \forall\, a \in A \\ q_w = \sum\limits_k f_k^w, & \forall\, w \in W \\ x_a = \sum\limits_w \sum\limits_k f_k^w \delta_{a,k}^w & \forall\, a \in A, \, \forall\, w \in W \end{cases}$$

Whereas SO and UE differ on the assumed driver behaviour both methods assume that all drivers have access to the information necessary to make travel decisions that perfectly align with the assumed traveller behaviour. While it is probable that daily users are equipped with the knowledge to roughly estimate the consequences of his or her route choices traffic is also composed of many travellers who travel between an OD-pair for the first time. Therefor it is somewhat unrealistic to assume that every user would be successfully in choosing a path with the lowest travel time. Though due to the massive technological progress over the past couple of decades, up to date traffic information is currently far more available to users of any traffic system than ever before. As a result, these assumptions on which both SO and UE assignment is built upon has become more realistic in recent times. Nevertheless, as long as humans operate the vehicles in a traffic system human error and unpredictability will always affect the route choices and consequently also the total system travel time. To combat this issue models which takes this into account, stochastic UE-assignment, were constructed (Daganzo & Sheffi, 1977). In other words, the difference between a regular and a stochastic UE-model is that in the former no individual can improve their travel time by changing their route while in the latter no individual believe that they can improve their travel time by switching routes. The imperfection of traveller's route choices is modelled through a logit distribution which affect the travel time to a different degree dependent on how well informed the travellers are assumed to be (Fisk, 1980). This model takes the form as:

$$min\ TT(x_a) = \frac{1}{\theta} \sum_w \sum_k f_k^w \ln f_k^w + \sum_a \int_0^{x_a} t_a(x_a) dx_a \tag{2.5}$$

Where:

θ: a constant representing the average users knowledge of the traffic system. $0 < \theta < \infty$

Similarly, to both UE- and SO assignment this formula is subjected to three constraints:

$$\begin{cases} x_a \geq 0, & \forall\, a \in A \\ q_w = \sum\limits_k f_k^w, & \forall\, w \in W \\ x_a = \sum\limits_w \sum\limits_k f_k^w \delta_{a,k}^w & \forall\, a \in A, \, \forall\, w \in W \end{cases}$$

Finally, it is important to note that all traffic assignment models covered in this chapter works under the assumption of a static traffic demand. This means that while the traffic demand may vary during different times of the day and different days of the week the demand reoccurs cyclical during the analysed period. There are also models which assume and model a dynamic traffic demand however these are not covered in this report.

2.3 Network Design Problems

As stated in *section 1.1*, RLSs is an alternative to reliving congested traffic systems by adding capacity to the road network through construction of new roads or new lanes on already existing roads. One of the major reasons as to why traffic assignment modelling is important, regardless if RLSs is applied or not, is that it can be used to identify where and how solutions can be implemented in order to improve a traffic system (Yang & Bell, 1998). This is defined as a *Network Design problem* (NDP) which by definition can be either continuous or discrete. An example of a continuous NDP is when the optimal solution for addition of new lanes on already existing roads are investigated. In contrast a discrete NDP deals with even more complex problems such as the optimal solution for addition of new roads to a traffic system.

Regardless of whether a NDP is of a continuous or discrete character they are still among the most complex mathematical problems within traffic engineering (Yang & Bell, 1998). This is because there are usually, many more variables than set relationships to calculate these variables. For example, in traffic network 1, *figure 1.2*, there are information available in terms of the traffic volume on each link. In that case this means seven sources of information. However, imagine that there are two viable paths between each OD-pair. That would mean that there are 60 $(2*(6*(6-1)))$ number of paths from which this traffic originates. As a result, there are usually many viable solutions to an NDP. This becomes increasingly problematic for larger traffic networks as the number of feasible solutions to a related NDP increase exponentially when size of a traffic network expands linearly. Due to this dynamic, addition of only one link to a traffic network may generated a large number of feasible solutions. As a result, it quickly becomes an insurmountable task to investigate all viable solutions manually, in order to find the optimal one. Instead, NDPs for larger networks are investigated through the use of mathematical programming models.

2.4 Programming

A programming model is basically lines of code which aim to explain to a program what actions will be executed (Hedman & Laaksonen, 1999). In mathematical terms programming models can be defined through many characteristics such as whether it is linear or non-linear and if there are any variables constrained to integer or binary values. Programming models can also work to optimize several objectives simultaneously. For example through a bi-level formulation, where there is dependence between the objectives.

To solve the objective of these types of model's computer algorithms are typically employed. An algorithm is a description of how to solve a computing problem (Kungliga Tekniska Högskolan, 2009). Whether or not the algorithm is able to solve a particular problem varies depending on characteristics of the programming model and the algorithm itself.

Due to the scale and complexity of NDPs, these problems are quite difficult to solve, even for a computer. Since a NDP can have millions of feasible solutions evaluating every single solution in order to find the optimal one can be very time consuming. Often the resulting computing time is unrealistically high. To combat this NDPs are solved with the use of *Heuristic algorithms* which may solve these types of problems within a reasonable timeframe (Kokash, 2005). This is because a heuristic algorithm is an algorithm which sacrifices accuracy to quickly arrive at a near optimal solution.

Obviously, it is preferable to find the optimal solution rather than a near optimal solution. However, the idea is that with millions of feasible solutions to evaluate it is improbable that the difference in quality between the best solution and a very good solution will be substantial enough to warrant the work associated with evaluating all feasible solutions. These near optimal solutions are found through local optimum points. Basically, a *local optimum* is a point which generates a better value than all locally surrounding points. The optimal points take the form of either maximum or minimum points, depending on how the objective function is formulated. In contrast a *global optimum* is a point which generates a value better than all other points, *figure* 2.2.

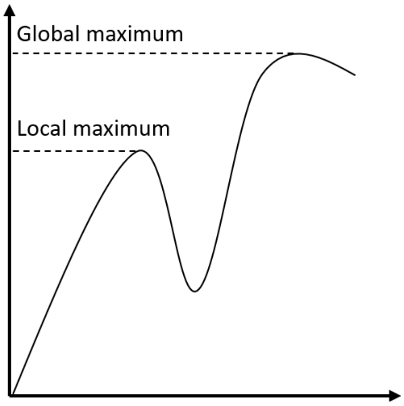


Figure 2.2: *Visualisation of a Global and Local maximum.*

However, these local optimum points also present a substantial risk for any heuristic algorithm. Since these algorithms are designed to find a near optimal solution rather than evaluating every possible solution there is a risk that the algorithm will stop investigating solutions outside of a local optimum and terminate itself based on the knowledge that all directly surrounding points generate worse values. While this is part of the efficiency of the heuristic algorithms it can also lead to unsatisfactory results. Whereas modern heuristic algorithms aim to reduce this risk (Kokash, 2005) it is still of great importance that the programming model which these algorithms are used on is sufficiently constrained to avoid arriving at a poor solution.

There are many types of Heuristic algorithms with some of the most common being:

- Tabu search algorithms: Which uses a memory system to restrict movement towards unfavourable solutions thereby limiting the amount of search paths for the algorithm (Pham & Karaboga, 2012).

- Swarm intelligence algorithms: Which simulates a collective intelligence system made up by individual agents. This optimization technique is similar to how some species of insects, such as ants, operate in real life (Ab Wahab et al., 2015).

- Evolutionary algorithms: Which evaluate an initial "population" of solutions and mimic natural selection and mutations to arrive at an optimal solution (Pham & Karaboga, 2012).

In evolutionary algorithms the problem is solved by mimicking natural selection through a population of so-called DNA strings. In mathematical terms the DNA string is defined as a vector filled with numbers which represent the value of each variable. For the first generation a population with completely randomized values are generated. The population is individually evaluated through their score in relation to the objective of the optimization, where penalties are awarded to individuals that do not fulfil the constraints. Once the evaluation is performed a new population is created where only the elite individuals are saved. All other individuals for the new generation are generated through either mutation, where one value in the vector "mutates" to a random number, or crossover where two parents exchange lines of values, *figure 2.3.*

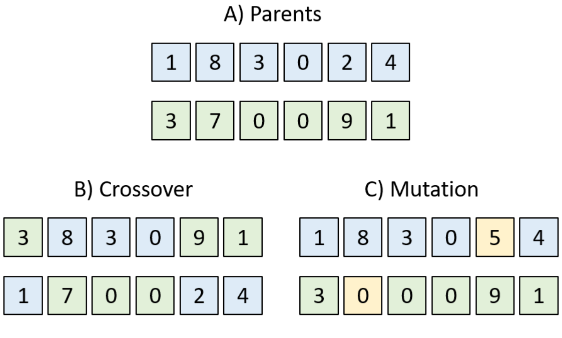
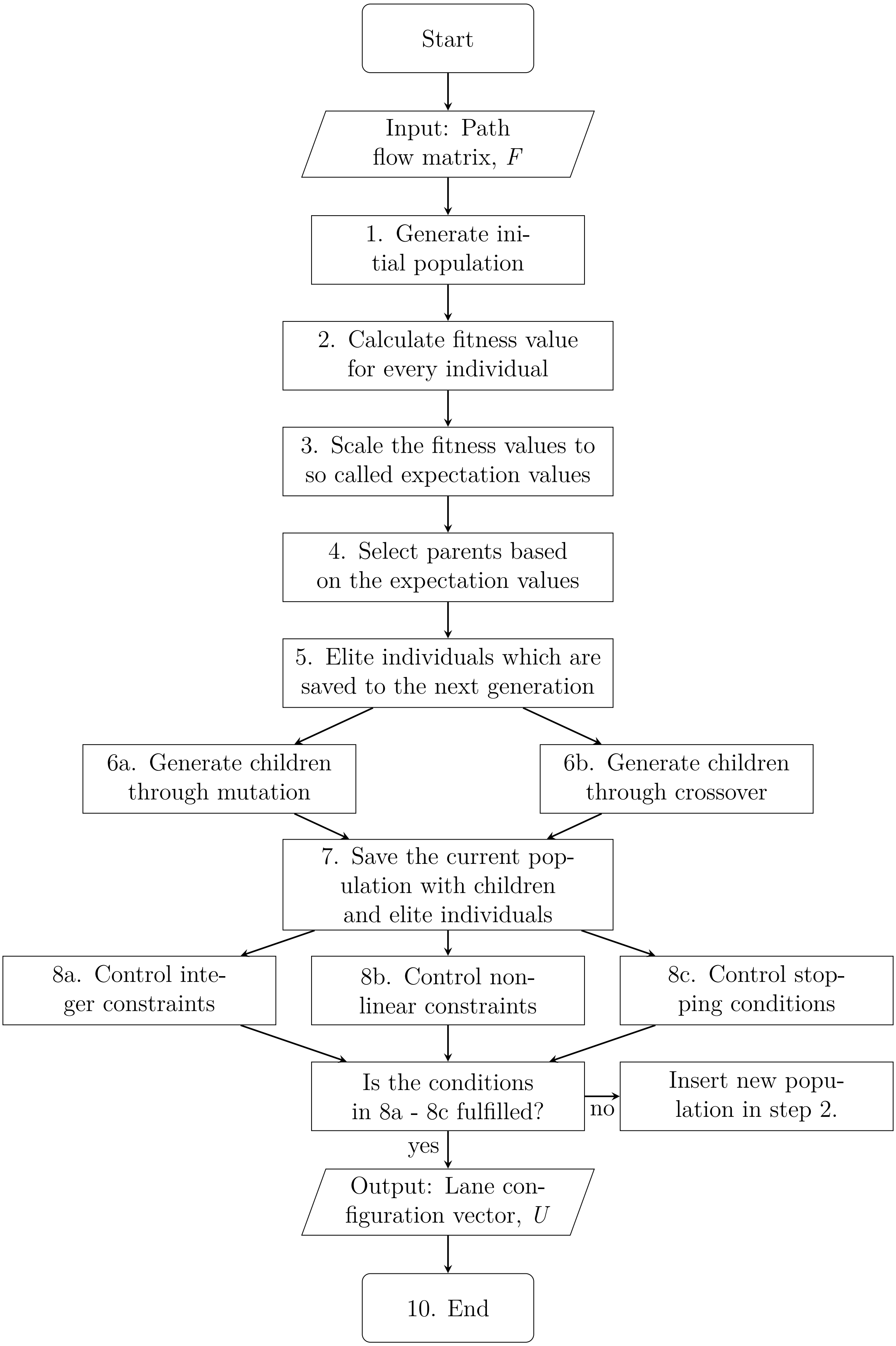


Figure 2.3: *Visualisation mutation and crossover in a GA.*

A full description of how a Genetic Algorithm (GA) operates, in this case the algorithm provided by MATLAB, is presented on the next page (MathWorks, Inc., 2022b).


Start
Input: Path flow matrix, F
1. Generate initial population
2. Calculate fitness value for every individual
3. Scale the fitness values to so called expectation values
4. Select parents based on the expectation values
5. Elite individuals which are saved to the next generation
6a. Generate children through mutation
6b. Generate children through crossover
7. Save the current population with children and elite individuals
8a. Control integer constraints
8b. Control nonlinear constraints
8c. Control stopping conditions
Is the conditions in 8a - 8c fulfilled?
no
Insert new population in step 2.
yes
Output: Lane configuration vector, U
10. End

3

Literature review

3.1 Literature review

Over the long period since RLSs were introduced there has been much research into evaluating the effectiveness of these systems. However, due to the constraints put upon this study in terms of time and space this research is not be covered in the literature review. Instead, the focus of the literature review is on the studies which aims to find methods and/or solutions for optimization in regards to implementation of RLSs.

As stated in the background RLSs has seen frequent use in the context of mass evacuation during the past decades. In relation to this some research has been conducted on optimizing the evacuation with the use of RLSs. Athanasios Ziliaskopoulos formulated this as a linear programming model with the aim to minimize the total evacuation time (Ziliaskopoulos, 2000). Ziliaskopoulos assumed that all vehicles were traveling towards the same destination, hence a linear programming model proved to be an effective option. In 2006 he and his colleague Hediye Tuydes would create another linear programming model also designed to find optimal placements of RLSs to minimize total evacuation time (Tuydes & Ziliaskopoulos, 2006). In this paper a Tabu-based heuristic algorithm were suggested and used to solve this problem. Another study which incorporates reversible lanes in the context of an evacuation is the 2010 paper written by Chi Xie and his partners (Xie et al., 2010). Xie and his colleagues suggest a bi-level programming model to find the lane configuration that generates the lowest possible evacuation time. In this model the upper level combines searching for the minimum evacuation time with cross-elimination constraints. The lower level represents a cell transmission-based dynamic traffic assignment problem. To solve this model the authors use a Lagrangian relaxation and a tabu search method.

One of the earliest studies to deal with a permanent reversible lane optimization problem was conducted in Greater Vancouver, Canada, in 1993 (Zhou et al., 1993). In this study Zhou and his colleagues investigated the optimal scheduling for an already existing RLS in the George Massey Tunnel. Zhou and his colleagues suggested the development of a dynamic RLS rather than the predetermined schedule which was used at the time. For the dynamic system a linear programming model was suggested which was programmed to vary the lane configuration in order to achieve the minimum total delay during the evening peak hours. To do this the algorithm used fuzzy logic prediction to find the traffic demand at different points of the evening peak. However, in the case of investigating the RLS in the George Massey Tunnel the optimal lane configuration is not taken into consideration. This is due to the fact that the configuration is already established and only one link is under investigation. Thus, the complexity of the problem is reduced significantly.

When it comes to optimizing the lane configuration in traffic networks, much research is based on the bi-level programming models developed by Yang and Bell to optimize NDPs. While this proposed methodology for NDPs only take addition of new links or lanes into consideration (Yang & Bell, 1998) the approach for traffic network optimization applies regardless of the optimization object. As such this methodology has been the foundation for many projects that followed it. One study which uses this bi-level structure to optimize the network design problem was the 2007 study conducted by Haozhi Zhang and Ziyou Gao (Zhang & Gao, 2007). Much like Yang and Bell the authors defined the upper level of the programming model to achieve the minimum total system cost while the lower level simulated route choices through stochastic user equilibrium assignment. To solve this the partners suggested a particle swarm optimization technique. In a similar study J.J Wu and his colleagues opted for a chaotic optimization algorithm to determine which and how many lanes should be adjusted in order to achieve the lowest possible total system cost (Wu et al., 2009). In the programming model the upper level incorporated flow entropy to accurately capture traffic behaviour and incorporated UE for the lower level under the assumption that the users could take part of an excessive traffic information system.

Chaotic solution algorithms were also used to solve a bi-level programming model in both a study conducted by Qing Li and Ziyou Gao in 2014 and by Xiao Liang and his partners in a 2011 of reversible lanes in central Beijing (Li & Gao, 2014) & (Liang et al., 2011). In the former, Li and Gao investigated the effect of implementing reversible lane technology in combination with a tradable credit system to cope with the current and decrease future traffic demand. In the latter the research group investigated if and how much reversible lane technology could reduce the traffic congestion on Chaoyang North Street and the surrounding links in eastern Beijing. In both programming models the lower level is represented by a stochastic user equilibrium. Though there is a slight difference in how the upper level is approached. Like Yang, the researchers Li and Gao assign the objective of minimizing the total system cost in the upper level (Li & Gao, 2014). In contrast, Liang and his colleagues use the upper level to minimize the network resistance which is defined as the relationship between traffic volume and road capacity (Liang et al., 2011).

These examples all assume a static traffic demand in the lower level of the programming model. However, a dynamic traffic demand can also be incorporated in this type of model. One such case is the 2008 paper named "Microscopic Traffic

Simulation Model-Based optimization Approach for the Contraflow Lane Configuration Problem" (Meng et al., 2008). Here the authors aim to construct a model to systematically identify which links are suitable for implementation of reversible lane technology. The optimal contraflow lane configuration is found by constructing a bi-level programming model where the upper level aims to minimize the total travel time while the lower level is represented by a microscopic traffic simulation model. As with most of the previous bi-level models the upper level consists of a binary integer programming formulation. To solve this model the authors use a genetic algorithm.

Similarly, a binary integer programming formulation is used by Ampol Karoonsoontawong and Dung-Ying Lin in the paper called "Time-Varying Lane-Based Capacity Reversibility for Traffic Management" (Karoonsoontawong & Lin, 2011). The authors also identify total system travel time as the objective for the upper level to minimize. Furthermore, the partners also use a Genetic algorithm to solve the proposed model and use a simulation (in this case VISTA) in the lower level to capture the dynamic behaviour of individual drivers. Though in the study conducted by Karoonsoontawong and Lin the schedule of the reversible lanes is also addressed whereas the paper written by Meng and his colleagues solely focused on the configuration of the RLS.

More recently Zhen Di and Lixing Yang constructed a bi-level programming model which incorporated a travel time budget (Di & Yang, 2020). In this model the drivers in the lower level would not fulfil their intended routes if the predicted travel cost exceeded their travel time budget. Trips that were initiated followed UE. Another thing that separates this methodology form other similar ones is that the authors opted to use coupling measure as the objective function in the upper level of the programming model. In this model the coupling measure is defined as the proportion of accessible flow and potential demand between two nodes. To solve the constructed model the authors use a heuristic algorithm. In contrast You and his colleagues proposed an alternative method for solving the network design problem (You et al., 2019). In this paper the authors proposed a histogram-based estimation of distribution algorithm.

In later years there has also been some research conducted on the interaction between RLSs and intersections. One such study investigated the use of reversible lanes as a means to increase capacity during evacuation if capacity constraints put on by intersections are taken into account (Mo et al., 2019). The authors found that not taking intersections into account resulted in an overestimation of the impact which reversible lanes generates on the total system travel time. Additionally, the model identified potential links where reversible lanes could be used effectively, which would have been missed had the constraints put on by the intersections not been taken into account.

Whereas RLSs can be optimized through the means of total system travel time there is also the possibility to use minimization of the queue length in intersections as an objective function (Lu et al., 2018). Here the queue length is used as the objective for the upper level in a bi-level programming model while the lower level uses stochastic user equilibrium to simulate the individual drivers. The model is solved with the use of a Monte Carlo algorithm. The interaction between reversible lanes and intersection is also the topic of the 2014 paper "Integrated design and operation of urban arterials with reversible lanes" (Zhao et al., 2014). Here the authors use the implementation of reversible lanes to maximize the flow within a signalized intersection.

In a recent study RLSs were also investigated in together with autonomous vehicles (Conceição et al., 2020). In contrast to many other solutions the authors utilised a mixed-integer non-linear programming model aim to investigate the benefits of implementing RLSs in addition to having all vehicles controlled autonomously in the Dutch city Delft. The authors assumed a static traffic demand and investigated the benefits under both user equilibrium and system optimum.

3.2 Conclusion literature review

In summation there are several ways to approach the network design problem of implementing reversible lanes. Though the most common solution is to formulate the problem as a bi-level programming model there is also many differences both in terms of defining the model and in how the model is solved with most efficiency and accuracy. Out of all definitions the most common method seems to be to define the upper level after minimizing the total travel time, assuming a static traffic demand and simulating the vehicle behaviour under user equilibrium. However, there are also several who argues that a dynamic traffic demand is more representative of traffic behaviour in practice. There are also several different methods for the reversal scheduling ranging from fixed to dynamic and different approaches in whether the limitations in traffic capacity caused by intersections are taken into account or not. A summation of the key components of some studies is presented in *table* 3.1.

Table 3.1: *Comparison of key components between papers in the literature review.*

Publication	Objective function	Traveler behaviour	Traffic demand	Algorithm
(Zhou et al., 1993)	Delay	-	Dynamic	Pattern prediction
(Ziliaskopoulos, 2000)	Travel time	SO	Dynamic	-
(Tuydes & Ziliaskopoulos, 2006)	Travel time	SO	Dynamic	Tabu-based
(Zhang & Gao, 2007)	System cost	Stochastic UE	Static	Intelligent swarm
(Meng et al., 2008)	Travel time	Micro-simulation	Dynamic	Evolutionary
(Wu et al., 2009)	System cost	Stochastic UE	Static	Chaos
(Xie et al., 2010)	Network performance	UE	Dynamic	Tabu-based
(Liang et al., 2011)	System resistance	Stochastic UE	Static	Chaos
(Karoonsoontawong & Lin, 2011)	Travel time	SO	Dynamic	Evolutionary
(Li & Gao, 2014)	System cost	UE	Static	Chaos
(Lu et al., 2018)	Queue length	Stochastic UE	Static	Monte carlo
(You et al., 2019)	System cost	UE	Static	Hb- distribution
(Di & Yang, 2020)	Network accessibility	UE	Static	-
(Conceição et al., 2020)	Travel time	UE & SO	Static	non-Heuristic

4

Method

The method chapter is divided into three different sections. In section 4.1 a mathematical model for evaluating the economic feasibility of a reversible lane system is formulated. Additionally, the assumptions that are taken into practice using this model are highlighted. In section 4.2 the method for defining the problem in a programming language, in this case MATLAB, is explained. Finally, in section 4.3 the implementation of the solution algorithm is explained.

4.1 Modelling

To accurately evaluate if and in those cases where it is economically profitable to implement reversible lane technology a mathematical model is created. For this the mathematical model needs to generate and accurately calculate the consequences for the traffic conditions as a result of implementing RLSs. In other words, the mathematical model needs to be able to:

1. Generate different configurations of RLSs in a traffic network.

2. Simulate the traffic distribution for every generated lane configuration.

3. Evaluate the economic costs and benefits for the generated lane configurations.

As with all mathematical model's reality is defined through constants and variables. For this particular model traffic networks are described through the relationships between a set of nodes, N, OD-pairs, W and travel demand, Q. The traffic network is also defined through a set of links, A, where the two directions of every road is defined as a separate links, a_{ij} and a_{ji}. To simplify the calculations the set of links is formulated as vector A' where only links existing links are included. In other words the vector A' is extracted from the matrix A and excludes all elements with a value of 0.

The model is formulated as a bi-level programming model where the objective of the upper level is to find the optimal investment of RLSs while the objective of the lower level is to distribute traffic in accordance with SO. For the upper level the variable that governs the lane configuration is defined as a set of lane configuration variables U:

$$U = \begin{bmatrix} u_1 & u_2 & \cdots & u_{a-1} & u_a \end{bmatrix}'$$

Where u_a is a denotation of the lane configuration on link $a \in A'$. The value of u_a is constrained to an integer value and is defined as:

$$u_a = \begin{cases} -1, & \text{If a lane is removed from link } a \\ 1, & \text{If a lane is added to link } a \\ 0, & \text{If the number of lanes on link } a \text{ is unaltered.} \end{cases}$$

The upper level of the programming model, which aims to maximize the economic output, is defined as:

$$\begin{aligned} max\ S(u_a) = 5 * h * y * d * g * \left(TT_0 - \sum_a t_a(x_a, u_a) * x_a\right) \\ - (p_0 + p_3 * d) * \left(2 * \frac{\sum u_a^2}{10^{-8} + \sum u_a^2} + \left\lceil \frac{\left(\sum u_a^2 * l_a\right) - 0.5 + 10^{-8}}{h_z * v_z * p_z} \right\rceil\right) \\ - 0.5 * (p_1 + d * p_2) \sum l_a * u_a^2 \end{aligned} \tag{4.1}$$

Which is constrained by:

$$\begin{cases} u_a \in \{-1, 0, 1\}, & \forall a \in A' \\ u_a(i) + u_a(i + \frac{l}{2}) = 0, & \forall\ i\ \in \{1, 2, ..., (\frac{l}{2} - 1), \frac{l}{2}\} \\ u_a \leq z_a, & \forall a \in A' \end{cases}$$

Where:

d: Constant for the amount of working weeks

g: Constant for the economic value of an hour in travel time [kr/h]

h: Number of hours that the RLSs are effective on a work day

h_z: Number of hours in which the zipper machines should reverse the direction in all RLSs

l: The number of links in A'

l_a: Length for every link a [m]

p_0: Constant for cost purchasing a zipper machine [kr/veh]

p_1: Constant for the investment cost for implementing RLSs [kr/m]

p_2: Constant for the operational cost of RLSs [kr/(m*work week)]

p_3: Constant for the daily operational cost of RLSs [kr/(m*work week)]

p_z: The proportion of time that the zipper machines are used to transfer barriers

$t_a(x_a, u_a)$: Average travel time on link a for traffic flow on and lane configuration of link a

TT_0: Total travel time for the traffic network before RLS is implemented [h]

u_a: Lane reversal decision variable

v_z: The velocity of the zipper machines when transferring barriers

y: The number of years

z_a: Indicator of whether implementing RLSs is feasibility or not

The feasibility indicator is defined as:

$$z_a = \begin{cases} 1, & \text{if feasible to implement a RLS on link } a \\ 0, & \text{Otherwise} \end{cases}$$

The first term in the upper level formulation calculates the economic gain as a result of the decrease in total system travel time. The model operates under the assumption that the RLSs generates a profit during every working day but not during the weekend. Thus, the hourly gain is multiplied with the number of working weeks. Furthermore, the hourly gain is also multiplied by the number of hours that the RLSs generates profit every work day. This factor should at least take the value of 2, representing the morning and the afternoon peak, but can be higher as well. The model is built around cost calculations in regards to a movable barrier system with zipper machines. Three types of costs are taken into account by the model. The initial costs of purchasing the zipper machines and implementing the barrier system (purchasing and installation). Additionally, the operational costs for running the systems which originates from both the amount of zipper machines and the length of the barrier system. The constants set for the operational costs should represent costs for maintenance, fuel, salaries and eventual exchanges. As seen in *equation 4.1* the operational costs is divided into two different terms. The former representing the costs for the barriers and the latter the costs for the zipper machine.

As the scale of the RLSs increase so will the amount of zipper machines needed to reset the system. At least two zipper machines are needed as long as reversible lanes is used anywhere in the traffic network. Though one could sufficiently complete the task for shorter lengths a additional zipper machine is always needed as a backup in case the first malfunctions. Once the length of reversible lanes exceeds that which one zipper machine can transfer between the peak hours the cost of another zipper machine is added. Naturally, calculations of zipper machines use rounding, since it is impossible to purchase half a vehicle. Thus, exceeding the length that an zipper machine can cover with as little as 1 m triggers the purchase of another machine.

In contrast to the profits, it is assumed that the operation generates costs during the entire day. Both the operational costs and investment costs are dependent on the length of the RLSs that are implemented. Thus, investment costs and the operational costs are defined through the units [kr/m] and [kr/(m*working weeks)]. This term is also multiplied with a factor of 0.5 as there are two links for every road.

The initial total system travel time is calculated through Wardrop's SO, *equation 2.3.* The same equation is used as the lower level of the suggested model. However, an additional constraint is added to ensure that the algorithm do attempt to lower the total system travel time by reducing the number of vehicles in the simulation. Mathematically this is formulated as:

$$\left\{\sum_{w}\sum_{k} f_k^w = PHT, \quad \forall\, w \in W\right.$$

Where:

PHT: The peak hour traffic volume

The travel time in both the upper and lower level of the model, *equation 2.4 & 4.1* is based on the BPR formula, *equation 2.2.* However, The BPR equation is altered so that the capacity of the roads, and the, travel time is dependent on a variable lane configuration, *equation 4.2.*

$$t_a(x_a) = t_0 + \alpha * t_0(\frac{x_a}{C_a + c_a * u_a})^{\beta} \tag{4.2}$$

Where:

c: The traffic capacity of one lane on link a

4.2 Defining the data

As stated in section 4.1, the only feasible way to solve this model, for medium to large networks, is to formulate it as a programming model. For this study the model is applied through the Global Optimization Toolbox provided in MATLAB. There are two approaches to defining an optimization problem with the Global Optimization Toolbox, solver-based approach and problem-based approach (MathWorks, Inc., 2022a). Here the mathematical solution is defined through a problem-based approach.

Information in MATLAB is defined and conveyed through matrices or vectors. As such, scalars are displayed in the form of a (1,1) matrix with a certain value. In the context of an optimization problem MATLAB differentiates between an input value and an optimization variable. Note that both can be defined as scalars, vectors or matrices. Regardless of the defined structure the input values have a set value whereas the optimization variable varies. For this problem the optimization variables are the set of lane configuration variables and the set of path traffic volumes, U & F while the other parameters are defined as input data. As most data used in this methodology is defined as either matrices or vectors it is vital that the dimensions of the defined data match. Otherwise, the mathematical operations cannot be performed. For this methodology the input data is defined as presented in *table 4.1*.

Table 4.1: *The necessary input data and the required structure of the data.*

Data	Type	Structure	Dimensions
α	Input data	Vector	$(l, 1)$
β	Input data	Scalar	(1,1)
δ	Input data	Matrix	$(l, m * (n^2 - n))$
C	Input data	Vector	$(l, 1)$
c	Input data	Vector	$(l, 1)$
d	Input data	Scalar	(1,1)
F	Optimization variable	Matrix	$((n^2 - n), m)$
g	Input data	Scalar	(1,1)
h	Input data	scalar	(1,1)
h_z	Input data	scalar	(1,1)
l_a	Input data	Vector	$(l, 1)$
N	Input data	Vector	$(l, 1)$
p_0	Input data	Scalar	(1,1)
p_1	Input data	Scalar	(1,1)
p_2	Input data	Scalar	(1,1)
p_3	Input data	Scalar	(1,1)
PHT	Input data	Scalar	(1,1)
p_z	Input data	Scalar	(1,1)
Q	Input data	Vector	$((n^2 - n), 1)$
t_0	Input data	Vector	$(l, 1)$
U	Optimization variable	Vector	$(l, 1)$
v_z	Input data	Scalar	(1,1)
y	Input data	Scalar	(1,1)
z_a	Input data	Vector	$(l, 1)$

Where:

l: The number of links in the network

m: The number of viable paths between each OD-pair in the network

n: The number of nodes in the network

Whereas the data can be defined directly in MATLAB it is generally easier to define it through excel and import it into MATLAB through the *readmatrix* command. For most of the data the explanations of dimensions are rather elementary. Nevertheless, for some data clarifications are essential to understand what the dimensions entail about the model.

For starters the OD-matrix, Q, is defined as a vector rather than a matrix. There are a couple of reasons as to why this structure is preferable to a matrix. Firstly, through this formulation the OD-pairs with no traffic demand (11, 22 and so on) can be removed from consideration. In contrast to a matrix structure where removal of these elements would cause a diagonal of empty elements through the matrix which is undesirable in matrix multiplication. Without the removal of these elements unnecessary rows full of zeros have to be added to the F- and δ-matrices just so the dimensions add up. Thus, the vector have $n^2 - n$ elements, where n is the number of nodes in the network. Secondly, and more importantly, this is necessary to sync the dimensions between Q, F and δ, allowing for matrix calculations. When transforming Q from a matrix to a vector each column is added one at a time to create a row vector. As such the elements are ordered in the following way:

$$Q = \begin{bmatrix} q_{12} & q_{13} & \cdots & q_{1n} & q_{21} & q_{23} & \cdots & q_{n(n-1)} \end{bmatrix}'$$

For the two optimization variables the structure of U is simply determined by the number of links in the traffic network. However, the structure of the path matrix F is more flexible. While the number of rows is set to match that of the OD-vector, Q, the number of columns is not determined by other data. The number of columns represent the number of feasible paths between OD-pairs. For a large traffic network, the number of feasible paths between each OD-pair is usually very high as the vehicles can traverse through a traffic network in many different ways. Though more realistic, it is very impractical and time consuming to define hundreds of feasible paths for each OD-pair. Especially since many result in travel times which renders these paths to be more or less unused anyway. To simplify the calculations, it is assumed that just a few of the viable paths between each OD-pair are used by the travellers. As such it is recommended that the number of columns in the path-matrix is set much smaller number. In this case the number of viable paths between each OD-pair is set to 2.

To ensure that matrix multiplication is possible the structure of the δ-matrix is entirely dependent on the structure of the OD-pair matrix, Q, the path traffic flow matrix, F, and the number of links in the network, n. To allow for matrix calculations the set number of paths used is the same for all OD-pairs. This is somewhat unrealistic as it is probable that there are more "logical" paths for travellers to use between two nodes that are on opposite sides of a city compared to two neighbouring ones. It is, however, vitally important that a viable path is defined in every row as leaving empty elements causes errors in the matrix multiplication. Furthermore, no rows or columns should be filled with only zeroes, to indicate that no path between these OD-pairs exists. This is important as matrix calculations are performed to define the problem constraints. A column or row including only zeroes in δ thereby generates an unconstrained element in the path traffic flow matrix, F. This causes both prolonged computing times and that the unconstrained element can take on any value in the span of $0 \leq f_k^w \leq \infty$. This does not affect the end result of the calculations as the full column of zeros in δ guarantees that this element is unused in all other calculations. However, controlling the results become more cumbersome if the value of one or several elements is completely randomized. If only one path exists between an OD-pair that path can be defined several times rather than leaving the "alternative" paths blank. While this means that distribution between the identical paths is to be randomized their sum is still constrained by the problem constraints.

A final piece of data which structure requires explanation is the LPF parameter β. As shown in *table 2.1* both α and β are standard values which vary depending on the characteristics on the link. However, in this methodology α is defined as a vector whereas β is defined as a scalar, *table 4.1*. Ideally, both should be defined as vectors since the values for both varies between different links. Though unfortunately MATLAB is currently unable to solve optimization problems where any exponent is defined as a vector or matrix. Since β is used as an exponent in the LPF, *equation 2.2*, it is defined as a scalar to avoid this. Whereas this allows MATLAB to process the problem it also negatively impacts the accuracy of the model. As the standard values of α and β varies to accurately reflect the travel time - traffic flow relationship on roads with different characteristics using the same values for all roads leads to poor approximations of the travel times. To minimize this issue the values of α are recalculated through a curve approximation process.

In this process the α and β values for all links are firstly selected from the standard values, *table 2.1*. The most frequent value of β is selected as the scalar value to be used in the model, β_1. The LPF for all links which already uses this β-value is unaltered. However, for the LPFs which initially had a different value of β the initial value of α is altered to a value which generates a as similar relationship between the travel time and the traffic flow as possible, α_1.

This is achieved through a *for-loop* in MATLAB. The for-loop calculates travel time for 50 values of the traffic flow evenly spread out between the traffic volumes of $0.5 * C - C$ for 2000 values of *alpha* between 0.1 and 2. The traffic flow stays in the interval of $0.5 * C - C$ as the peak traffic is most likely to be within this span. Apart from these travel volumes being unlikely there are also additional motivation for why very low and very high traffic volumes are not included in the LPF approximation. At low traffic volumes the travel time is close to the FFTT, hence the travel time is only marginally affected by the change in parameters at this state. In contrast the calculated travel time for traffic volumes exceeding the capacity is very much affected by the change in parameters. However, as the travel time increase rapidly for traffic volumes above the road capacity the effect of congestion is still intact. In other words, even though the calculated travel time might be an over- or underestimate compared to the original LPF there is still be a substantial difference in calculated travel time for the large traffic volume and the FFTT. Thus, travellers still avoids using routes where the traffic volume exceeds the capacity in the calculations.

The value of β is set to the value of β_1. This generates a travel time vector with 50 elements for each α-value between 0.1 and 2. Using these vectors, the loop calculates the average difference between all elements in these vectors to a travel time vector calculated with the initial parameter values, α & β. Lastly the loop evaluates which value of α_1 generates the best approximation of the original travel time - traffic flow relationship. Mathematically this process is described as:

$$min\ S_t(\alpha_1) = \sum \sqrt{(t_1 - (t_0 + t_0 * \alpha_1 * (\frac{x_a}{C})^{\beta_1}))^2} \tag{4.3}$$

Where:

t_1: The travel time calculated using the initial values of α & β

Where the vector representing the difference in travel time is raised to the power of 2 and then square rooted so that all elements are positive. This is important as the difference in absolute value is the interesting aspect.

4.3 Solution Algorithm

As previously mentioned, the model is solved with the Global Optimization Toolbox within the program MATLAB. Unfortunately, this comes with some restrictions that forces reformulation of the suggested model in order to comply with the limitations of this programming language. Within this toolbox, the only algorithm capable of solving this mixed-integer nonlinear of optimization problems is the Genetic Algorithm (GA), (MathWorks, Inc., 2022b). A description of how this algorithm operates is presented in *section 2.4*. Since this GA cannot work with both integer and equality constraints the constraints within the model have to be reformulated. As both lane configurations and traffic volume have to be defined as integers (there cannot be 7.4 cars on a road after all) the equality constraints are reformulated into inequality constraints. For *equation 4.1* the constrains is reformulated as:

$$\begin{cases} u_a, & \in \{-1, 0, 1\},\ \forall a \in A' \\ u_a(i) + u_a(i + \frac{l}{2}) \leq \quad 0.5, & \forall\ i\ \in \{1, 2, ..., (\frac{l}{2} - 1), \frac{l}{2}\} \\ u_a(i) + u_a(i + \frac{l}{2}) \geq -0.5, & \forall\ i\ \in \{1, 2, ..., (\frac{l}{2} - 1), \frac{l}{2}\} \\ u_a \leq z_a, & \forall a \in A' \end{cases}$$

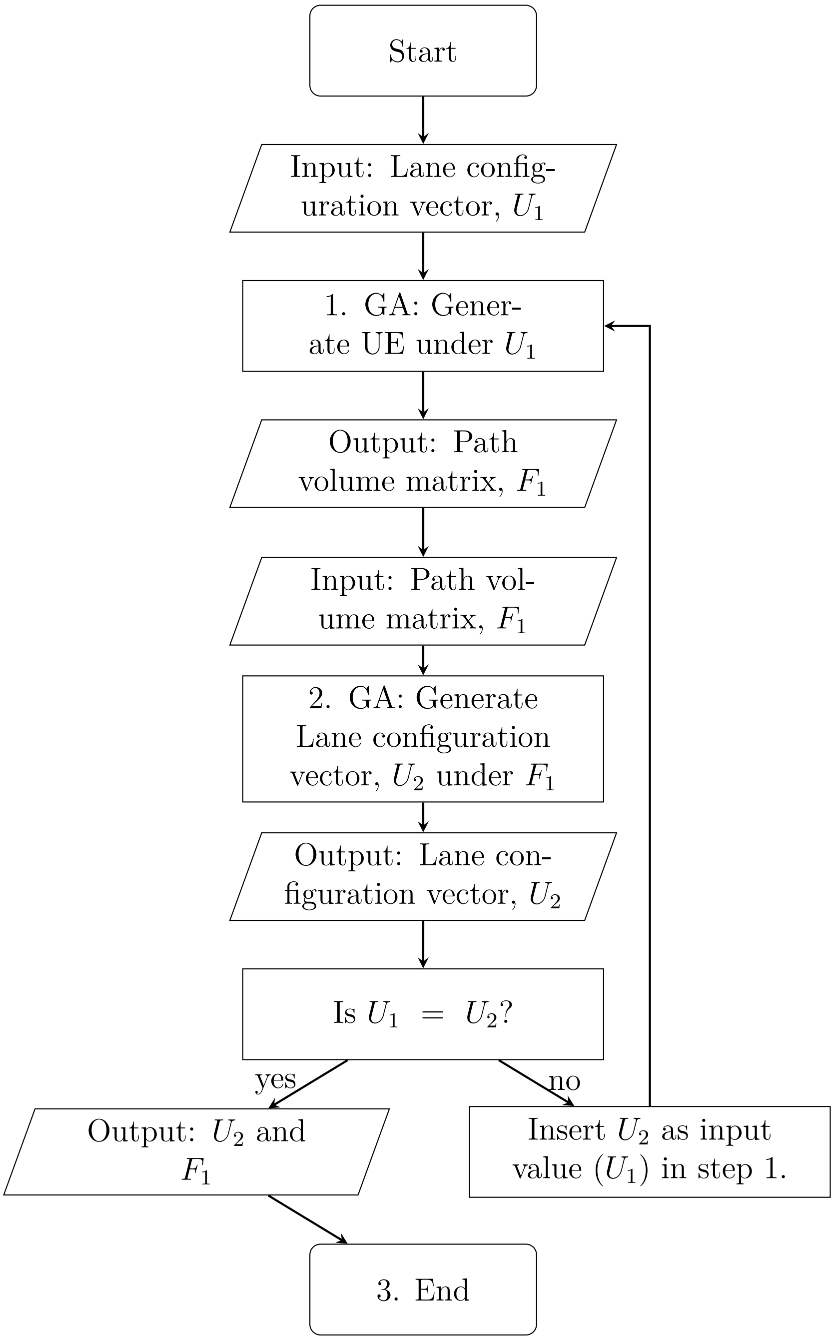
As all element in U is restricted to only take on scalar values these constraints generate the same effect as the equality constraint. While a decision variable, which are constrained to only take on binary values, are often used this type of heuristic algorithm also works with a variable constrained by continuous integer constraints. However, the same mathematical effects could be achieved by using two decision variables.Here one would govern adding a lane to a link while the other would govern removing a lane from a link.

For the SO, *equation 2.3*, the equality constraints are defined within a span of 2 cars. This span aids the algorithm to find feasible starting points. These constraints are reformulated as:

$$\begin{cases} x_a \geq 0, & \forall\, a \in A' \\ q_w + 1 \geq \sum\limits_k f_k^w, & \forall\, w \in W \\ q_w - 1 \leq \sum\limits_k f_k^w, & \forall\, w \in W \\ x_a + 1 \geq \sum\limits_w \sum\limits_k f_k^w \delta_{a,k}^w, & \forall\, a \in A',\ \forall\, w \in W \\ x_a - 1 \leq \sum\limits_w \sum\limits_k f_k^w \delta_{a,k}^w, & \forall\, a \in A',\ \forall\, w \in W \\ \sum\limits_w \sum\limits_k f_k^w \ \geq PHT - 1, & \forall\, w \in W \\ \sum\limits_w \sum\limits_k f_k^w \ \leq PHT + 1, & \forall\, w \in W \end{cases}$$

However, the most problematic consequence of using MATLAB's Global Optimization Toolbox for this particular model is that MATLAB do not provide an algorithm that is capable of solving Mix-integer bi-level programming problems within their Optimization Toolboxes (MathWorks, Inc., 2022a) & (MathWorks, Inc., 2022c). To comply with the restrictions of the algorithms provided by MATLAB to problem has to be reformulated either by removing the integer constraints or by removing the bi-level formulation. Since the problem cannot function without the integer constraints the bi-level structure is separated into two different optimization problems.

The main difference with when separating the problems is that the lane configuration and the total system travel time no longer is optimized simultaneously. Instead, both problems require input data that is collected from the results of the other problem. In other words, what was formerly the upper level, *equation 4.1*, requires a path volume matrix, F, to generate a lane configuration vector, U. Similarly, what was formerly the lower level, *equation 2.4*, requires a lane configuration vector, U, to generate a path volume matrix, F. To arrive at an optimized state an iterative process is conducted where the output from *equation 4.1* is used as input in *equation 2.4* and the output from *equation 2.4* is used as input in *equation 4.1*. This process is repeated through enough iterations until the optimized state is achieved. It can be initiated by either input of a U_a vector or a F matrix. Schematically this methodology is defined as:



While this methodology can generate a optimized result in the end it is severely limited compared to a bi-level formulation. This is because unlike the bi-level formulation the travel behaviour of the vehicles is not updated simultaneously as the lane configuration vector. As a result, all new lane configurations are measured with its performance under the travel behaviour left from original lane configuration. While this does not automatically mean that the algorithm finds the original lane configuration to be the best one it increases the risk that other lane configurations are overlooked. Indeed, some of these lane configurations could generate a better system travel time if the change in travel behaviour is implemented under that lane configuration. To alleviate some of these issues an additional constraint is introduced that forbids the lane configuration from being composed of only zeros. Once the path flow is optimized for this lane configuration one can truly know if the original lane configuration is indeed a more optimal solution. Mathematically this constraint is formulated as:

$$\begin{cases} \sum_a u_a^2 \geq 0, \quad \forall\, a \in A' \end{cases}$$

5

Case Study

In this chapter the proposed methodology is applied through a case study where the economic prospects of implementing RLSs are evaluated. The case study is performed over two scenarios, one for the collected traffic volumes and one simulating a 2040 scenario. In *section 5.1* the traffic network is presented while *section 5.2* provides an in-depth overhaul of the collected and calculated input data for the model.

5.1 Traffic network setup

For the case study 36 nodes are identified as vital for the traffic system of Gothenburg, *figure 5.1*. These points vary from between intersections as well as entry and exit points from highways.

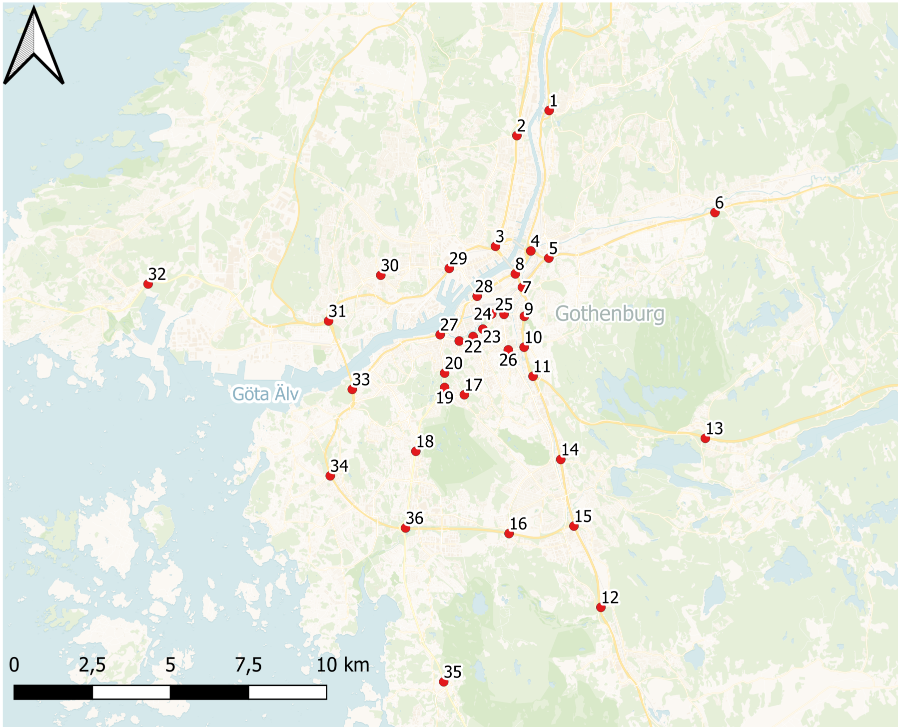


Figure 5.1: *The nodes used in the case study.*

Secondly, the major roads which directly connect these points are identified. In total 50 roads are used, *figure 5.2.* As all roads allow traffic to travel in both directions a total of 100 links are used in the case study.

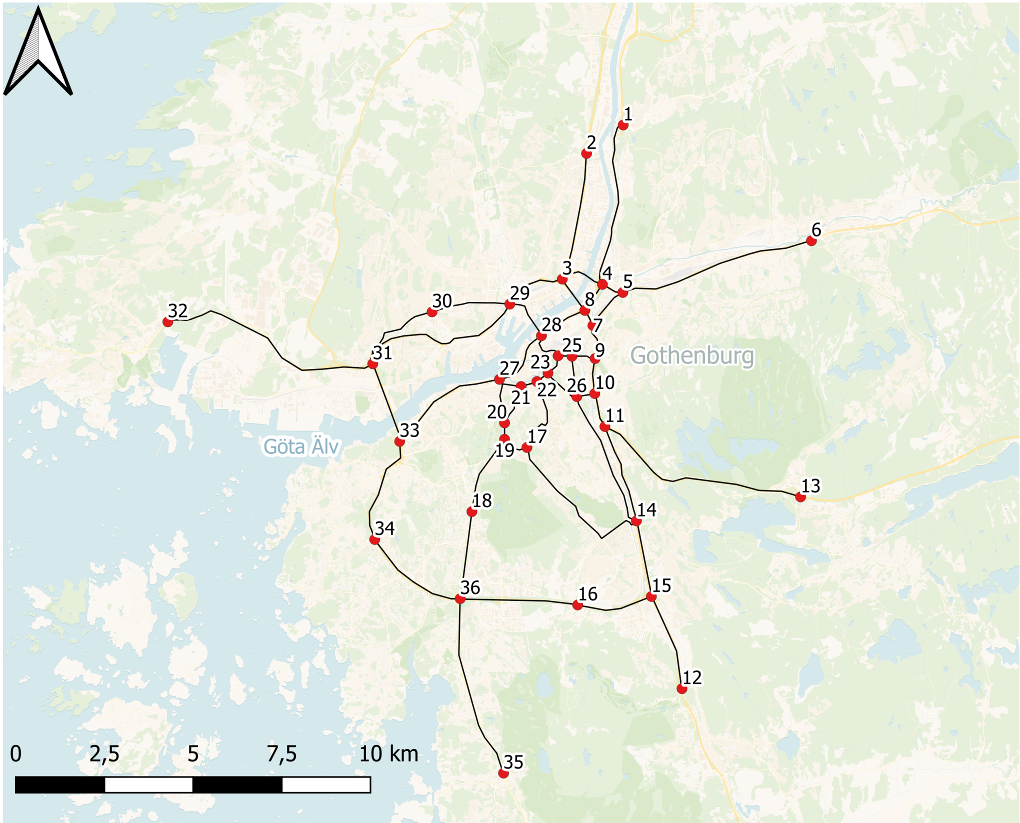


Figure 5.2: *The nodes and links used in the case study.*

With this information the path-matrix, δ, is defined. It is assumed that there are two viable paths between each OD-pair. Thus, a total of 2520 viable paths is defined for this traffic network.

5.2 Collection of data

As with most studies one of the main challenges is collecting relevant and reliable data. In this case study much of the necessary input data is not directly available for collection. Instead, this data is calculated and/or approximated. The procedures for collection, calculation and approximation of all used data are described throughout the rest of this chapter.

5.2.1 Practical feasibility

The practical feasibility is evaluated through the use of Google maps (Google, 2022). Construction of RLSs is deemed to be infeasible if large reconstruction of the road is necessary to implement RLSs. While this does not mean that is not possible the incitement of lower investment cost than construction of new roads disappears. There are several reasons as to why reconstruction might be necessary. A common reason is that the travel directions are separated by, for example, trams, tunnel walls, or parks. Another reason as to why it could be infeasible is that the link for the two travel directions are located on different elevations. A full description of how the feasibility for all links is presented in *table A.1* in *Appendix A*.

5.2.2 Link length approximation

The link lengths are approximated through the *Measure* tool in the program *Qgis*. Here Google maps has been used as the reference map, (Google, 2022). The full set of link lengths is presented in *table A.1* in *Appendix A*.

5.2.3 FFTT calculations

The free flow travel time for each link is calculated using a regular time-speed-distance relationship, *equation 5.1.* Here, it is assumed the free flow travel speed, v_0, is equal to the speed limit which is provided by the Swedish Transport Administration (Trafikverket, n.d.-a). There are a few links for which the speed limits are not provided in this data-base. In these instances, the speed limits were collected by finding a speed limit sign for those roads on google street view (Google, 2022). A complete list of the collected speed limits and the calculated FFTTs is presented in *table A.1* in *Appendix A*.

$$t_0 = \frac{l_a}{v_0} \tag{5.1}$$

5.2.4 Calculation of road capacity

For the road capacity calculations both the *U.S. Department of Transportation's* simplified highway capacity calculation methods and the *Swedish Transport Administration's* guide for capacity calculations are used (U.S. Department of Transportation, 2017) & (Trafikverket, 2013). For this the links in the traffic network are defined into one of four different categories:

- Freeway: Defined as a road with at least two lanes in each direction which are divided by a barrier and has full access control. Furthermore, freeways are typically level with no grades exceeding 2%.

- Multilane highway: While highways in practice often are very similar to freeways, the design of highways are more flexible. For example, highways do not have full access control and can thus have vehicles enter through intersections rather than ramps. Furthermore, highways are not always divided by a barrier.

- Urban highway: The Multilane highways with 2-3 lanes and a speed limit between 70-100 [km/h]. For these links the Swedish Transport Administration's guide for capacity calculations are used.

- Signalized highway: A highway where traffic signals are used in the intersection.

Generally, the American methods for capacity calculations are used rather than the Swedish's counterparts. This is mainly due to the used formulation for the travel time are also provided by the American State. However, in the case of highways set in urban areas the *U.S. Department of Transportation* notes that the formula for the Multilane highways tend to overestimate the road capacity (U.S. Department of Transportation, 2017). This is quite the problem since this case study only investigates highways set in the urban area of Gothenburg. As such the capacity for the links defined in this set is calculated using the *Swedish Transport Administration's* instead. However, as these methods only covers the highways with 2-3 lanes with a speed limit of 70-100 km/h the American methods for Multilane highways are still used in some instances.

In the case of the regular roads that are analysed in this study, they too are categorized in accordance with to options stated above. In all of these instances signalized intersections were present and thus all regular roads are categorised as a signalized highway. As the cycle structure of the intersection is heavily influences the capacity of these roads the problems with using a method designed for highways on smaller roads are somewhat alleviated. However, there is still a substantial risk that the capacity for regular roads is overestimated due to the use of this methodology. Though this method is still preferred over other methods which calculates road capacity either as a function of headways, as a function of more detailed road characteristics or through intersection simulation. The first relies on either heavy assumptions or detailed measurements neither of which are ideal for this study. The second and third requires an extensive inventory of the intersection and traffic signal characteristics which is not possible within the time limit of this study.

Five parameters are taken into account for defining the roads in this study. These are, access control, signalized intersections, number of lanes, inclination and speed limit, *table 5.1*. There are instances where the characteristics of a road do not fit perfectly with this template in which case the best possible fit is used. A complete list of how each link is categorised is presented in *table A.2* in *Appendix A*.

Table 5.1: *The lowest and highest speed limit for the road types in the case study.*

Road type	Access control	Traffic signals	Lanes	Inclination	Speed limit
Freeways	Yes	No	≥ 2	≤ 2 %	Any
Multilane Highways	No	No	≥ 2	Any	Any
Urban Highways	No	No	2-3	Any	$70 - 100$
Signalized highways	No	Yes	Any	Any	Any

The information regarding the Access control and presence of traffic signals are collected through a combination of the Swedish Transport Administration's traffic network map and the street view of Google Maps (Trafikverket, n.d.-a) & (Google, 2022). Additionally, the information of the number of lanes and the inclination of the roads is also collected from the maps provided by the Swedish Transport Administration (Trafikverket, n.d.-a). In the case of the inclinations, the highest average value for slopes exceeding 200 meters in length is used as the inclination for the link. As such it is possible for the links in opposite directions on the same road to also have the same inclination if the road travels both uphill and downhill. Note that it is not the absolute value that is interesting so any negative inclination is naturally described as ≤ 2 %. For all capacity calculations the capacity for a single lane is rounded to the nearest increment of 50 which both ensures that the capacity value is an integer and also makes the calculations more standardized.

The total capacity for the freeways in the traffic network is calculated through the use of *equation 5.2*. As the formula uses the unit [miles/hour] in the original form the equation is modified to work with speeds of the unit [km/h].

$$C = \left\lfloor \frac{2200 + 10 * (min(70, \frac{FFS}{r}) - 50)}{1 + \frac{HV}{100}} \right\rceil_{50} * N \tag{5.2}$$

Where:

FFS: The free flow speed [km/h]

HV: Adjustment factor for percentage on heavy vehicles on the road [decimal]

N: Lanes on the road

r: Constant for converting from [miles/h] to [km/h] (1.609344)

Similarly, to the freeway capacity calculations the formula for the Multilane highways is modified to work with speeds of the unit [km/h], *equation 5.3*.

$$C = \left\lfloor BC * f_{hv} \right\rceil_{50} * N \tag{5.3}$$

Where:

BC: Base capacity

f_{hv}: Adjustment factor for heavy vehicles

The base capacity is defined as:

$$BC = \begin{cases} 1000 + \frac{20}{r} * FFS, & if\ FFS \leq 96,56\ [km/h] \\ 2200, & Otherwise \end{cases}$$

Additionally, the adjustment factor for heavy vehicles is calculated through *equation 5.4*:

$$f_{hv} = \frac{1}{1 + P_T(E_T - 1)} \tag{5.4}$$

Where:

E_T: Passenger car equivalent per heavy vehicle

P_T: Proportion of heavy vehicles

This procedure is very similar to that of the Swedish Transport Administration method for calculation of standard values for urban highways. However, this calculation instead finds a base capacity value for the full capacity of the road rather than a base capacity for each lane. In this analysis this is problematic since that means that there is a risk that the capacity of each lane does not become an integer which is of the utmost importance in the lane configuration calculations. To work around this the Swedish Transport Administration's method are reformulated, *equation 5.5.*

$$C = \left\lfloor \frac{BC_N}{N} * f_{hv} \right\rceil_{50} * N \tag{5.5}$$

Where the base capacity is collected from the standard values provided by the Swedish Transport Administration, *table 5.2.*

Table 5.2: *The total Base capacity for different types of Urban Highways.*

Type of highway	Speed limit [km/h]	Total Base Capacity
Urban 2 lanes	70	4050
	80	4250
	90	4360
	100	4460
Urban 3 lanes	70	5600
	80	5800
	90	5900
	100	6000

For the calculations of the capacity for the Multilane highways the value of E_T is set through the guidelines provided in the book *The Principals of Highway Engineering* *and Traffic Analysis* (F. L. Mannering & Washburn, 2013). In contrast the values for the calculations of the Urban highways are taken from the guidelines of provided by the Swedish Transport Administration (Trafikverket, 2013). In the former the value varies dependent on the environment around the road whereas in the latter the inclination is the determining factor, *table 5.3.* Since there is no exact inclination provided for the categories in the former these are assumed.

Table 5.3: *Passenger car equivalents for different types of terrains.*

Type of highway	Inclination [%]	Terrain	E_t
Multilane highways	≤ 2	Level	1.5
	2-3	Rolling	2.5
	3-4	Rolling	2.5
	≥ 4	Mountainous	4.5
Urban highways	≤ 2	Level	1.3
	2-3	Rolling	1.3
	3-4	Rolling	2
	≥ 4	Mountainous	2.6

For the signalized highways the capacity is independent of the speed limit. Instead, the capacity depends on the effective green time of the traffic signals. Though as this formula is applied to regular roads rather than highways it is still a considerable risk that the capacity calculated with this formula is an overestimation of the actual capacity. To minimize this issue the formula is reformulated to implement the base capacity calculations from the Multilane highway calculations, *equation 5.6*

$$C = \left\lfloor \frac{g_t}{T_c} * BC \right\rceil_{50} * N \tag{5.6}$$

Where:

g_t: Effective green time for traffic movement [sec]

T_c: Total cycle length [sec]

As there is no information publicly available on either the total cycle length or the effective green time these values are all assumed to equal the default values for calculations in the U.S Department of Transportation's manual for highway capacity calculations, (U.S. Department of Transportation, 2017). Here the total cycle length and effective green time varies depending on significance of the roads. However, according to this guide for standard values the default relationship between the cycle length and the effective green time is 0.5 regardless of which type of road it is designed for.

Using the Swedish method for capacity calculations the total capacity is calculated without first calculating the capacity for each lane. To guarantee that the individual lane capacity are integers the total capacity is recalculated using, *equation 5.7*. The calculated capacity for each link is presented in *table A.4* in *Appendix A*.

$$C = \left\lfloor \frac{C_0}{N} \right\rceil_{50} * N \tag{5.7}$$

Where:

C_0: The initial total capacity

5.2.5 Collection of Traffic volumes

The majority of traffic volumes are collected from Gothenburgs open access database regarding the measurements of traffic flows on roads in the city (Göteborgs Stad, n.d.-b). Here the average daily traffic flows and the traffic flows during the afternoon peak hour are provided for both directions of the roads. Moreover, the speed limits and the median speeds of the vehicles is also recorded. As the RLSs are most likely only going to be used during the peak hours the peak hour traffic flows are used for the calculations.

However, the city of Gothenburg does not operate every road within the municipality boarders. Some of the highways in the city are owned and operated by the Swedish Transport Administration (Göteborgs Stad, n.d.-a). Accordingly, there is no records of the traffic volumes on these roads in the Gothenburg traffic flow data-base. These traffic flows on these roads are instead collected from the traffic measurements made by the Swedish Transport Administration (Trafikverket, n.d.-b).

While both of these databases are quite thorough, they lack data regarding the peak afternoon traffic volume, x_a, for some links. Additionally for some links latest measurement of peak hour traffic that is publicly available is from as far back as 1998. In the cases where only a very old measurement exists the values of the traffic volumes are adjusted by multiplication with a traffic development factor. The values for this factor are derived from the travel development reports provided by the city of Gothenburg (Göteborgs Stad, 2011) & (Göteborgs Stad, 2018). As there has not been a significant increase in the traffic volume throughout the 2010s in Gothenburg any value collected in this decade is not adjusted. For older measurements the traffic adjustment factors used are presented in the table below, *table 5.4*.

Table 5.4: *Adjustment factor for calculation of traffic volumes for older measurements.*

Year	Adjustment factor
1998	1.150
2002	1.054
2004	1.015

In the instances where there is no measurement available, the traffic volumes are calculated with Average Daily Traffic Volume, $ADTV$, which is available for all roads. For the roads that lack information regarding x_a it is assumed that the proportion of x_a and ADTV is equal to the average proportion of the between x_a and ADTV among the roads where information for both traffic volumes are available. As such the peak traffic volume for the roads that lack this information is calculated using *equation 5.8*.

$$x_a = 2 * Pd * ADTV_a * \frac{\sum x_1}{\sum ADTV} \tag{5.8}$$

Where:

$ADTV_a$: The average daily traffic volume for link a

$ADTV$: The average daily traffic volume of all links where information of the peak traffic volume is available

Pd: The peak hour direction parameter

x_1: The collected values of the peak traffic volumes

Where the peak hour direction parameter is defined as

$$Pd = \begin{cases} 0.53, & \text{If } x_a \text{ is in the direction towards the city center} \\ 0.47, & \text{Otherwise} \end{cases}$$

The value of Pd is derived by calculating the average traffic volume split between the road's direction towards and from the city. For this the node n_{23} is defined as the central point in the city, *figure 5.1*. A full description of the direction of the links is presented in *table A.1*.

Similarly, to the peak hour volumes, the volumes of heavy vehicles are not presented for all roads. For these roads the proportion between the number of heavy vehicles and ADTV is assumed to be equal to the average proportion between the heavy vehicles and ADTV for the roads where this information is available. Mathematically this is expressed as:

$$HV_c = ADTV_a * \frac{\sum HV_m}{\sum ADTV} \tag{5.9}$$

Where:

HV_c: The calculated proportion of heavy vehicles on the a link a

HV_m: The collected values of the proportion of heavy vehicles on the link a

Note that the ADTV-values and the heavy vehicle volumes often are presented as the sum of total traffic in both directions. In these cases, it is assumed that the traffic is evenly split between the two directions. Thus, the ADTV-value and the heavy vehicle traffic volume is divided by two and used for both link a_{ij} and link a_{ji} in these cases.

5.2.6 LPF parameters

With the use of the calculated lane capacities and the collected speed limits the initial values of the LPF parameters (α & β) are chosen from the standard values, *table 2.1*. The most common value of β is chosen as the scalar to represent the β-value in the calculations. The α-values for all links that does not have the chosen β-value as the initial β-value is modified using the curve approximation method described in *section 4.2*.

While there is no way to gain an exact replica of the relationship, as the β-values are different, this method generally results in much better approximations compared to only changing the β-value and keeping the original α-values. For this study this methodology tends to generate functions which underestimates the travel time below the capacity but overestimates the travel time above the capacity. A example of this is presented in *figure 5.3* which displays the altered travel time traffic flow relationship for Tingstadstunneln. A full list of all initial and calculated α- & β-values, for the links where the constants are adjusted, are presented in *table A.3* in *Appendix A*.

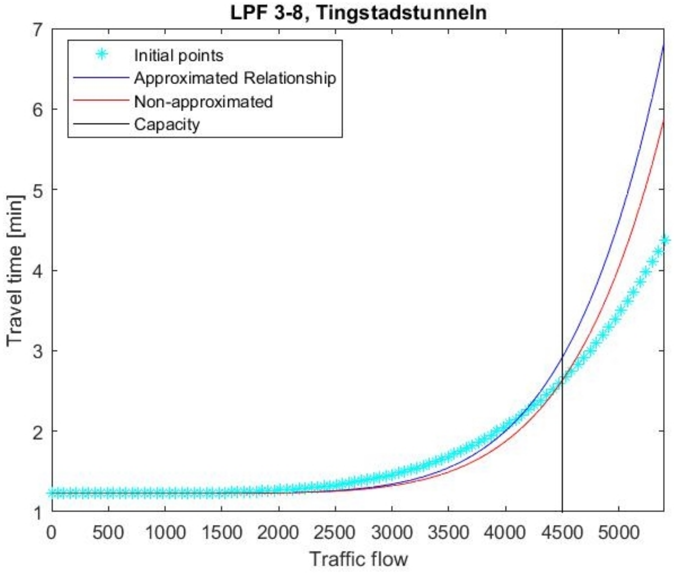


Figure 5.3: *The resulting curve approximation for example link 3-8.*

5.2.7 Calculation of OD-demands

Currently Gothenburg do not provide information regarding the OD-demand in the city. This is not surprising as the OD-demand is notoriously difficult to measure as it requires much resources of many traffic sensors or personnel (KTH, 2021). Instead the OD-matrix is calculated with the use of the collected traffic flows. The matrix is redefined as a vector and is calculated using the Genetic Algorithm in MATLAB. For this a initial total travel time, TT_0, is calculated where x_a are the collected link flow values. With this information an optimisation problem is defined which minimizes the difference between the initial travel time and a travel time formulation dependent on a variable path matrix F, *equation 5.10.*

$$min\ S_{tt}(x_a) = (TT_0 - \sum_a \int_0^{x_a} t_a(x_a)dx_a)^2 \tag{5.10}$$

Constrained by:

$$\begin{cases} x_a \geq 0, & \forall\, a \in A' \\ x_a = \sum\limits_w \sum\limits_k f_k^w \delta_{a,k}^w, & \forall\, a \in A',\, \forall\, w \in W \\ \sum\limits_w \sum\limits_k f_k^w \geq PHT - 1000, & \forall\, w \in W \\ \sum\limits_w \sum\limits_k f_k^w \leq PHT + 1000, & \forall\, w \in W \\ \sum\limits_k f_k^w \leq 250, & \forall\, w \in W \end{cases}$$

Where the third and fourth constraint ensures that there are a credible number of cars in the system which take credible paths. Without this constraint the algorithm tends to find solutions where the value for as many paths as possible is zero. This entails that the path is not used by anybody. This is problematic since this results in an OD-matrix where the vast majority of trips are between neighbouring OD-pairs. Naturally this is somewhat unrealistic as the need to use a car decreases for lower distances. The span for the constraining number of cars is found by calculating the average proportion between the peak traffic volume and the total daily traffic volume for all links in the traffic network. This proportion is multiplied to the number of total daily trips for the entire city of Gothenburg. Note that this does not result in the total amount of cars active in Goteborg during the peak hour but rather a realistic estimation of the number of cars it takes to generate the measured peak hour traffic. Note that only the traffic volumes for links in the analysis are taken into account. Since there are many roads in Gothenburg which are not included in this analysis the real peak hour traffic volume is likely to be much higher.

$$PHT = \frac{500\,320}{\sum\limits_{a} ADTV_a} * \sum_{a} x_a \tag{5.11}$$

The final constraint has a similar effect as it ensures that the demand between an OD-pair may not exceed 250 vehicles. Similarly to the previous constraints, this counteracts the issue that the algorithms tend to find solutions with as many zeros as possible which results in the majority of the demand existing between neighbouring OD points.

The OD-demand vector, Q, is calculated through a summation of the columns in this feasible path flow matrix, *equation 5.12*.

$$q_w = \sum_{k} f_k^w \tag{5.12}$$

For the 2040 scenario the same procedure is performed where the traffic volumes and the peak hour traffic volume are increased to 125% of the collected traffic volumes. This is the predicted increase by the Swedish Transport Administration (Trafikverket & Göteborgs Stad, 2019).

5.2.8 Determination of cost constants

As the aim of the model is to determine the best possible investment of RLSs in a traffic system, the terms that measures the costs and profits are naturally of high importance. The way in which the model is constructed the term that generates value to society represents the value of the decrease in total system travel time, g. For this case study this value is collected from the guidelines for socio-economic analysis within the transport sector provided by the Swedish Transport Administration (Trafikverket, 2020). The Swedish Transport Administration provide several different valuations for different types of journeys. A business trip is, for example, valued higher in economic terms than a private trip to work. Since the RLSs are mainly used during peak hours, which most commonly occur when people travel to and from work, the most appropriate value for this case is the term that represents *private trip to work within congestion.* According to this report the economic value for society for every saved hour of congestion of one car in this category is 153 kr or about 14 euros. Since the model calculates the travel time in minutes this value is converted to 2.55 [kr/min].

The cost of implementing and running the reversible lane system is likely to vary significantly from case to case. Especially as there are several methods which can be used to achieve reversibility for the lanes. In this case study the implementation of a RLS using movable barriers is investigated. For these four types of cost is taken into account. On the investment part both the investment cost for purchasing zipper machines and the investment cost of buying and installing the barriers themselves are taken into account. Furthermore, tow weekly operational cost is used which together represents everything from maintenance costs as well as fuel and salaries for the zipper vehicle drivers. For this study the typical investment cost for RLSs derived from the estimation by the cooperation *Lindsay Transportation Solutions* is used (Rathbone, 2017) & (World Highways, 2018). For the purpose of this study the values of the investment costs and the operational cost is converted to the currency the *Swedish crown*. At the time of this study the exchange rate between the Swedish crown and the American dollar is 9.42. While estimated costs are five years old, at the time of performing this study, the costs are not adjusted to any potential inflation in America between 2018-2022. In accordance with the recommendations provided by *The Chamber of Industry and Commerce of Western Sweden*, the yearly operational costs are calculated as 7.5 % of the investment costs (Västsvenska Industri- och Handelskammaren, 2010). The converted constants are presented in *table 5.5.*

Table 5.5: *Cost estimations for constructing RLSs with movable barriers.*

Cost	Cost type	Unit	Value
Zipper machines	Investment	[kr/machine]	15 072 000
Movable barrier	Investment	[kr/m]	8 154
Operational cost barrier	Operational	[kr/(m*work week)]	12
Operational cost zipper machine	Operational	[kr/work week]	21 738

5.2.9 Determination of zipper machine constants

Similarly to the investment costs for the barriers, the zipper machines operational speed is collected from the cooperation *Lindsay Transportation Solutions* (Lindsay Transportation Solutions, 2019). As the manufacturer claims that the upper limit of the speed is 15 [km/h] it is assumed that the average speed is somewhat lower, 14 [km/h] to be precise, *table 5.6.* As the direction of the lanes should be reversed between 9 am and 4 pm the value for h_Z is set to 6. Here a 1 hour lunch break is accounted for. It is assumed that the zipper machine is actually used to reverse lanes for 50% of this time. The rest of the time is naturally used to travel between roads where the lanes should be reversed and initiating the reversion process.

Table 5.6: *The constants regarding the zipper machine.*

Constant	Cost type	Unit	Value
v_z	Vehicle speed	[km/h]	14
h_z	Time to reverse lanes	[h]	6
p_z	Usage rate	[-]	0.5

5.2.10 Time period constants

As previously stated, it is assumed that the RLSs generates economic value at two hours each day, the morning and afternoon peak. The case study is formulated to investigate the economic prospects over a 10 year period for the date the systems becomes operation. It is assumed that the system only is operational for 47 weeks a year to account for a five week period during the summer where most Swedish employees are on vacation.

5.3 Simulation

With the values of all input data collected or calculated the simulations are performed in accordance to the method presented in *Chapter 4*. Four different types of simulations are performed. In two of them, only the lower level is applied as SO is generated for the 2022 and 2040 without implementing RLSs. In the other two the optimal lane configuration and SO is generated for the 2022 and 2040 scenario. A full summary of all input data is presented in *Appendix A*.

6

Simulation Results

The results are divided into several parts. First some collected information about the study area are presented, *section 6.1*. Secondly, the simulated travel behaviour and the optimal lane configuration for the 2022 scenario are presented, *section 6.2 & 6.3*. Similarly, the simulated travel behaviour and the optimal lane configuration for the 2040 scenario are presented in *section 6.4 & 6.5*.

6.1 Lane Variability

As previously stated, it is not always economically, spatially or practically feasible to construct an RLS. This is the case for many of the major roads in central Gothenburg, *figure 6.1*.

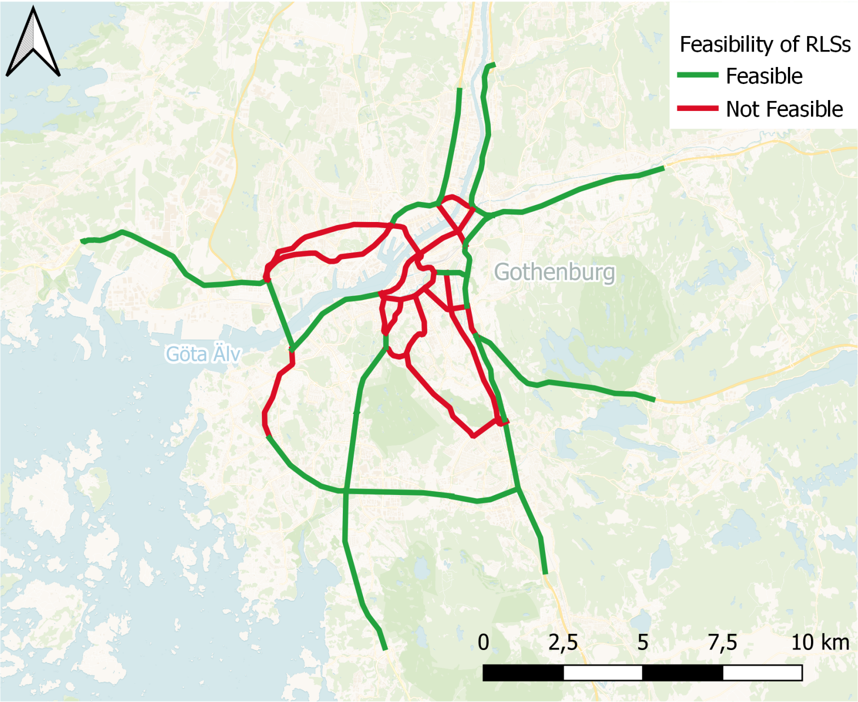


Figure 6.1: *The lane feasibility in the traffic network.*

In most of these cases RLSs is infeasible due the directions being separated either by tunnel walls or trams. Generally, the construction of RLSs are least feasible within the most central parts of the city whereas it generally are feasible for the major highways that connects the city centre to larger metropolitan area. Similarly, to this pattern, the number of lanes is also generally lower for the most central parts of the city, *figure 6.2*. Though the number of lanes do, in most cases not exceed 2 even for the city's highways and freeways.

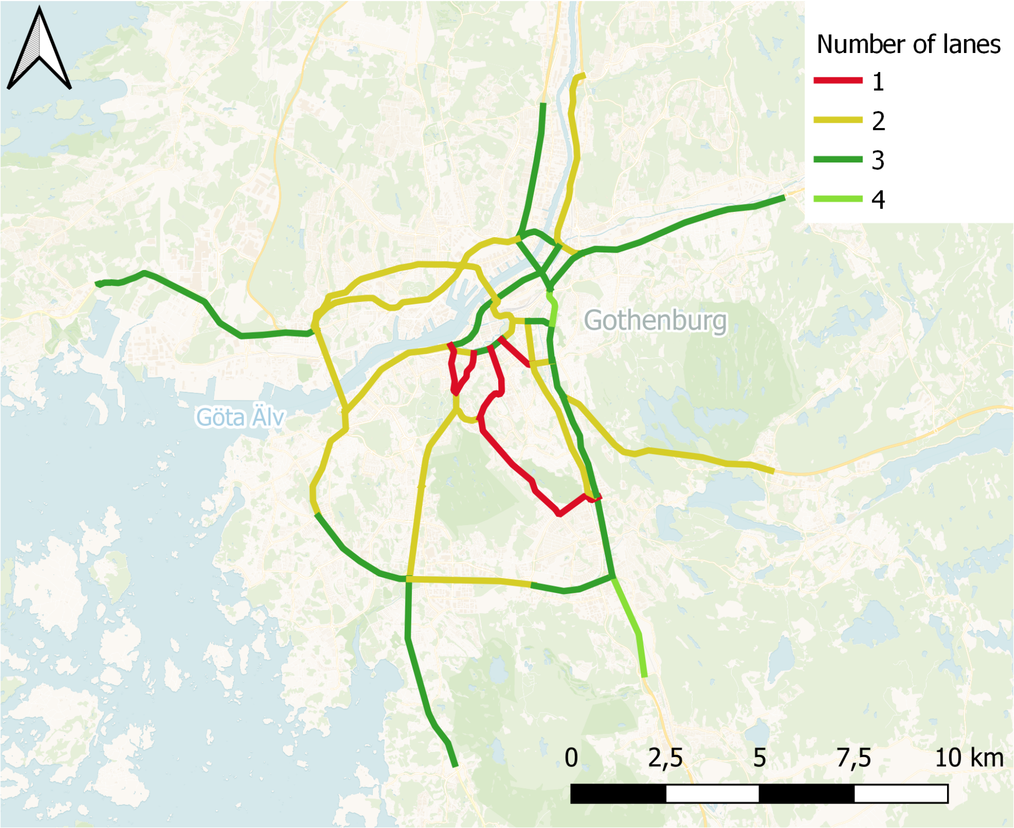


Figure 6.2: *The number of nodes for all links in the traffic network.*

6.2 Simulated travel behaviour 2022

The preliminary calculations for the case study results in a utilization which is presented in *figure 6.3*. In general, the calculated utilization rates are below 75%, which is where travel time starts to increase due to congestion.

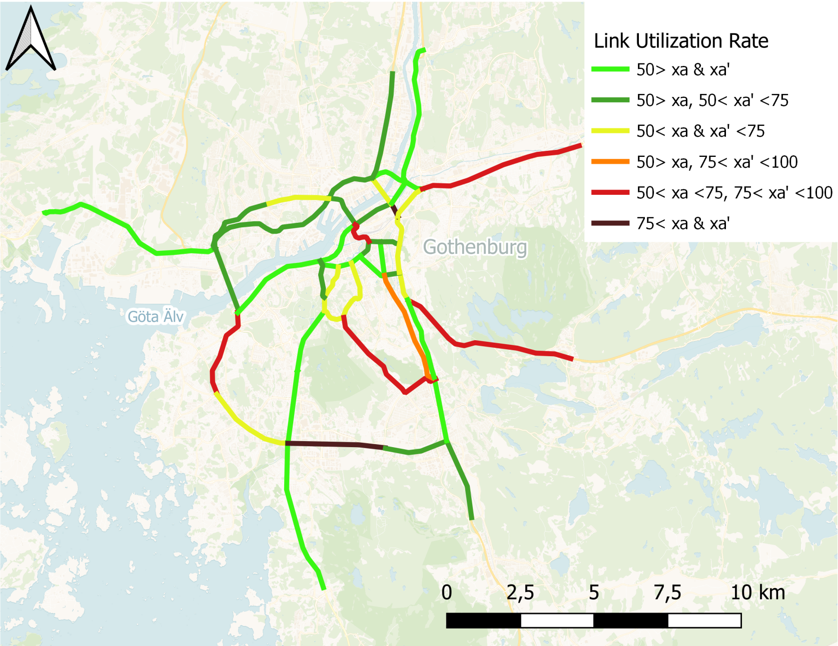


Figure 6.3: *Link utilization rate in the traffic network 2022.*

The travel behaviour, generated through these traffic volumes, is presented through an OD-matrix which is presented in *table A.5* in *Appendix A*. According to the calculations most of the traffic is generated in close proximity to where large traffic flows are found, *figure 6.4*. Moreover, only a small part of the traffic originates in the most central nodes of the city.

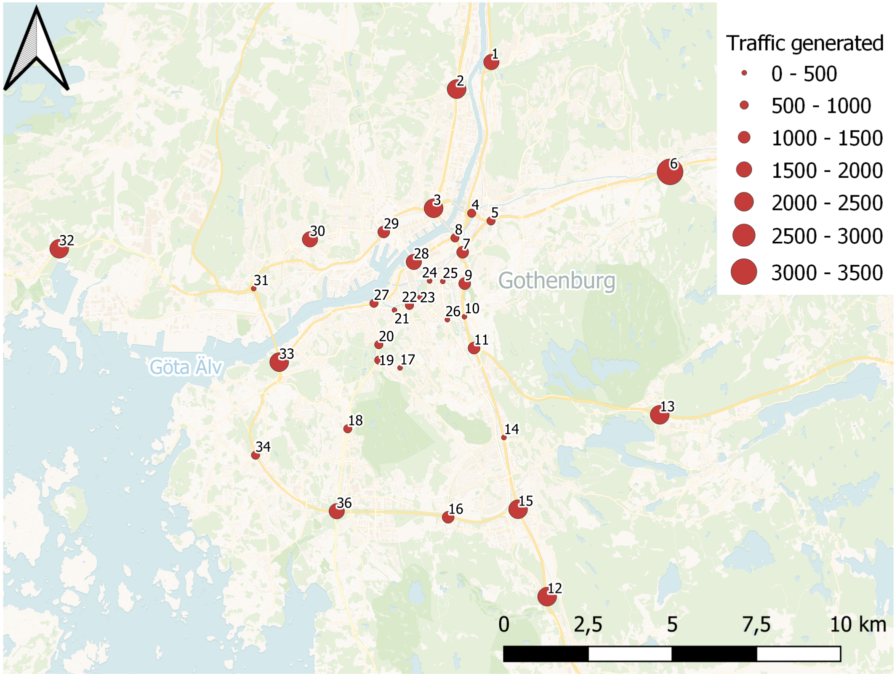


Figure 6.4: *The traffic generated from all nodes in the traffic network 2022.*

The pattern for the attracted traffic is even more clear. A vast majority of the traffic volume are attracted to the nodes that are located on the highways which connects Gothenburg to other urban areas within the metropolitan area of Gothenburg, *figure 6.5*. However, the attracted traffic volumes are not always fixated to links with the larges traffic volumes. For example, a very low traffic volumes are attracted to the inner point of the E6 freeway, node 11, even though a large traffic volume passes through that point.

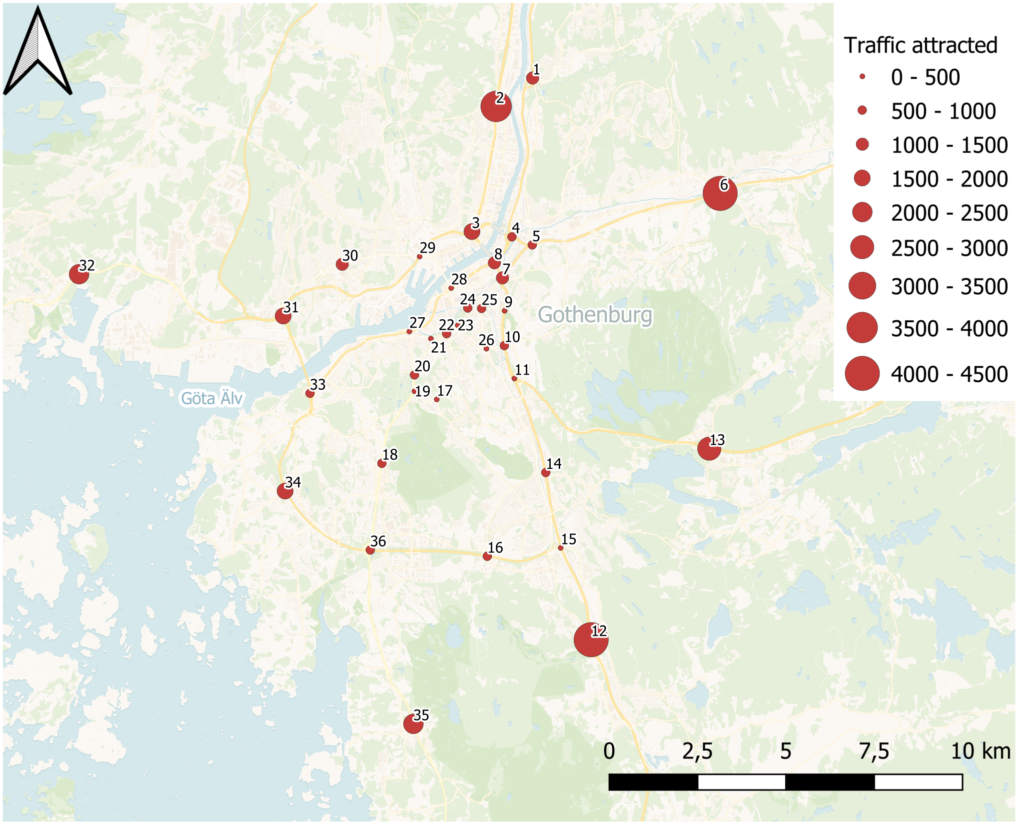


Figure 6.5: *The traffic attracted to all nodes in the traffic network 2022.*

6.3 Lane configurations 2022

Using the iterative process following lane configuration is generated, *figure 6.6*. The process is two iterations long before the same lane configuration is generated.

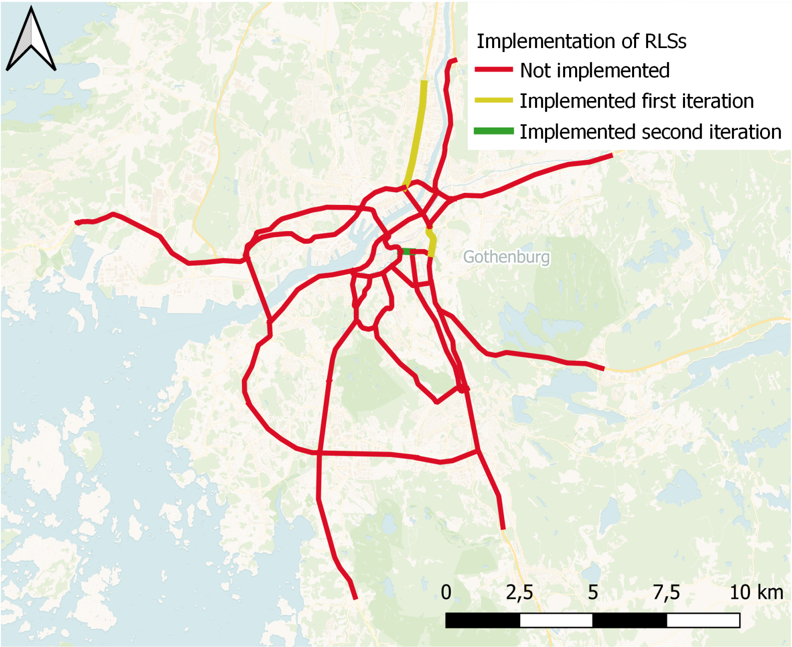


Figure 6.6: *The economically optimal lane configuration for 2022.*

As a result of the change in lane configuration the travel behaviour in the traffic network changes. A complete table including all generated traffic volumes and the corresponding travel times is presented in *table A.7* in *Appendix A*.

As the travel behaviour becomes more efficient it is probable that the sum of the traffic volume on each link decreases. This is because the vehicles will choose shorter paths to their destination, thus using fewer links (unless it is preferable to take longer paths in terms of travel time). For the 2022 scenario the amount of traffic on all links do not change significantly, *figure 6.7*.

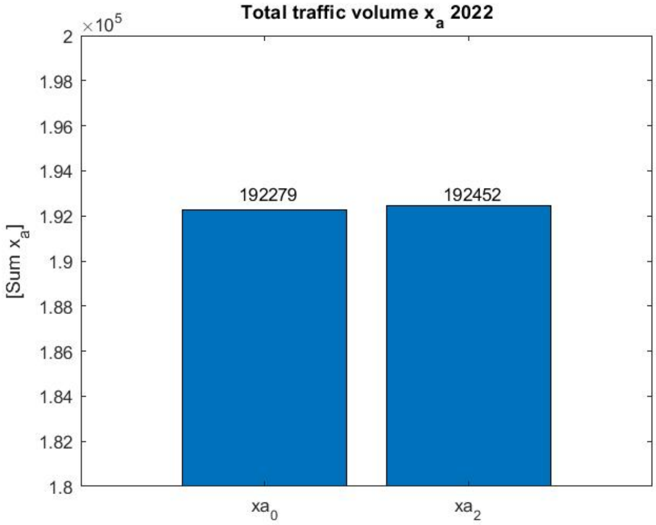


Figure 6.7: *The total number of vehicles on the roads in the traffic network.*

Using the collected traffic volumes, the total system travel time amounts to 395 660 minutes during every peak hour, *figure 6.8*. However, this is not the optimal distribution of the traffic. When optimising the traffic system without any additions in form of reversible lanes the minimum total traffic volume is calculated to 373 230 minutes. For the first iteration of the lane configuration a higher total system travel time is generated. Though for the second iteration a lower system total travel time, 372 833 minutes, is achieved.

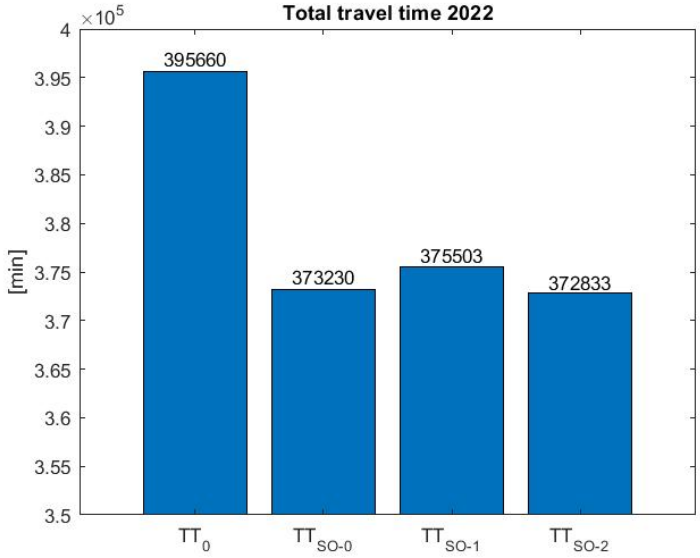


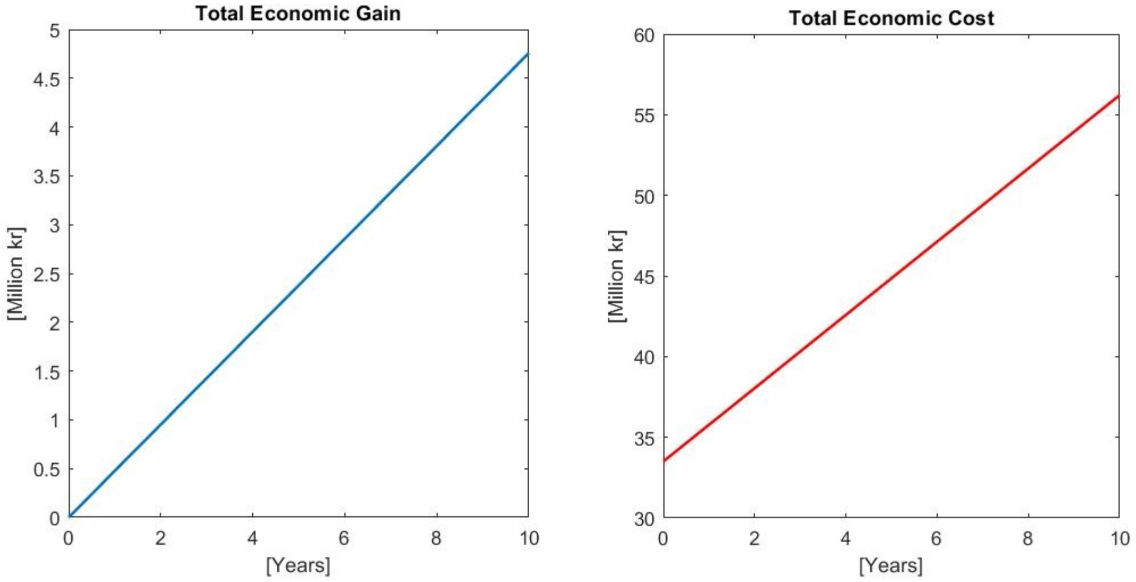
Figure 6.8: *The total travel times for different lane configurations.*

With this lane configuration a RLS is implemented on a 412-meter-long stretch of *Ullevigatan*. Accordingly, only two zipper machines are necessary to operate the RLS. In total the RLS would cost about 33 400 000 kr to install and have average daily operational and maintenance cost 9 664 kr, *table 6.1*. In contrast the time saved during the daily peak hours is only valued at about 2 000 kr.

Table 6.1: *Cost estimations for constructing RLSs with movable barriers.*

Type	Value	Unit
Zipper machines	30 144 000	[kr]
Movable Barrier	3 359 448	[kr]
Daily Operational cost	9 664	[kr/day]
Daily value generated	2 025	[kr/day]

Naturally, this means that this system would not be economically profitable. Over a period of ten years the system generates a societal value of about 5 million kr, *figure 6.9a*. However, during the same period the combination of the investment, operational and maintenance costs amount to about 56 million kr, *figure 6.9b*.



(a) *Economic gain.* **(b)** *Economic cost.*

Figure 6.9: *The expected economic gain and costs for the RLS over a ten year period for the 2022 scenario.*

This means that while the investment cost is about 34 million implementing this system would generate a net loss of about 50 million kr for 10-year period, *figure 6.10*.

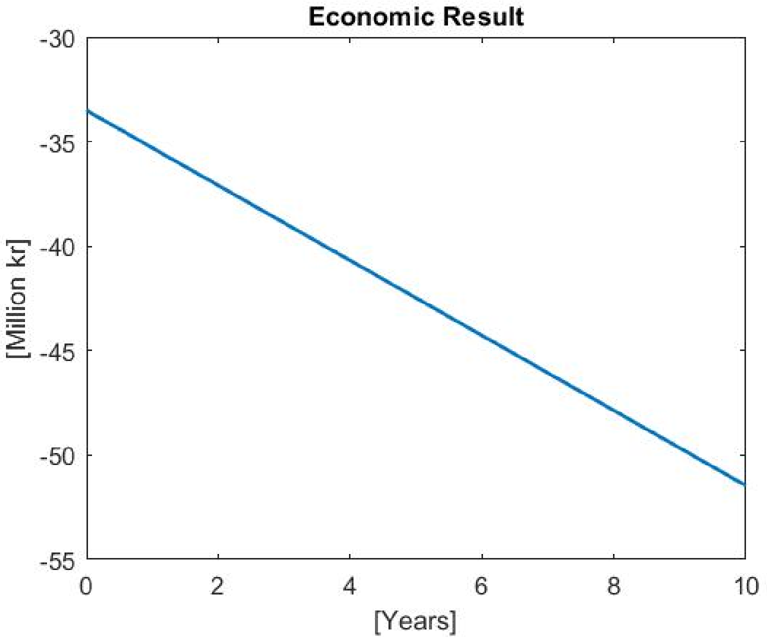


Figure 6.10: *The expected economic outcome for the optimal RLS strategy over a ten year period for the 2022 scenario.*

6.4 Travel behaviour 2040

With all traffic volume increased by a factor of 1.25 the utilization rate is naturally higher for the 2040 scenario than for the 2022 scenario, *figure 6.11*.

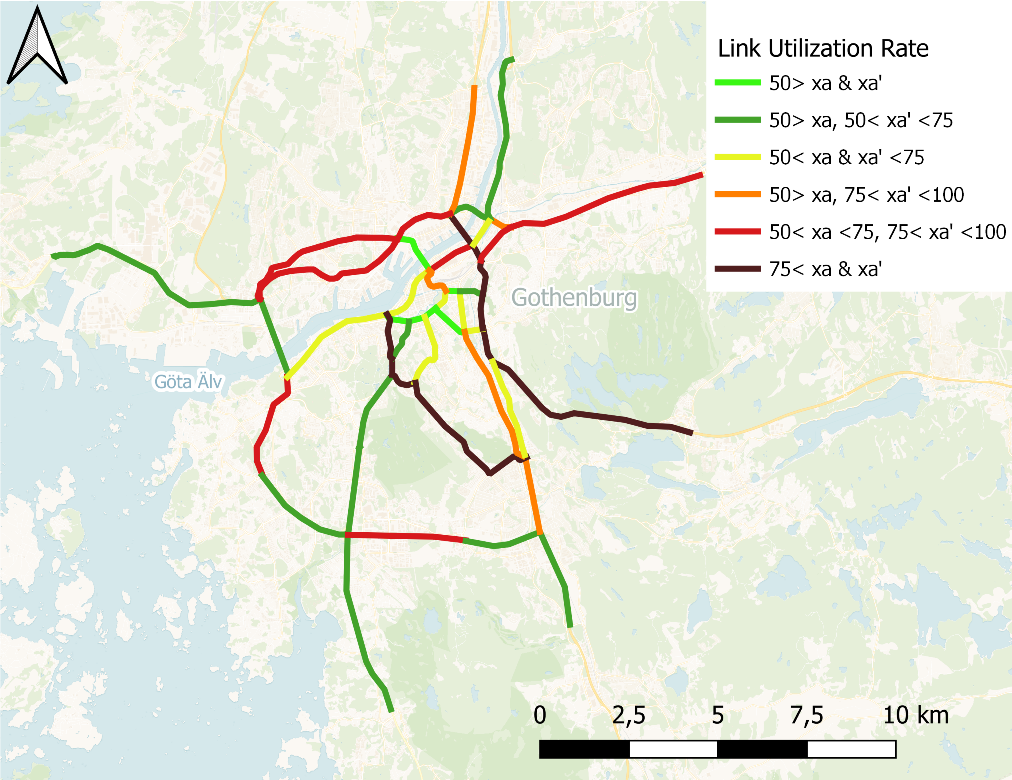


Figure 6.11: *The utilization rate for the 2040 scenario.*

However, there are still little to no increase in travel time for most of the roads in the traffic network. Though on roads affected by congestion the travel time is usually affected on both links. In other words, there are few roads where congestion is asymmetrical and affects the travel time.

As with the 2022 scenario most of the traffic is generated outside of the city, *figure 6.12*. It is also clear that traffic is generated in close proximity to links exposed to large traffic volumes. As with the 2022 scenario the generated OD-matrix is presented in *Appendix A*.

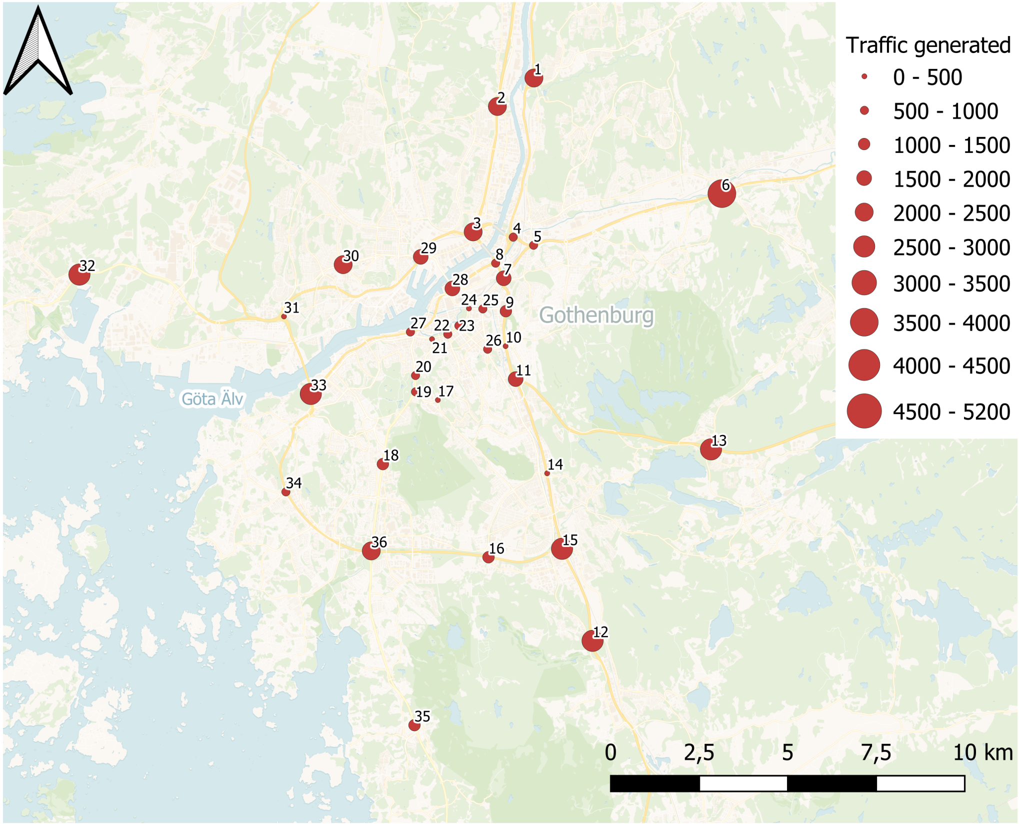


Figure 6.12: *The traffic generated from all nodes in the traffic network 2040.*

This pattern is also clear for the attracted traffic volumes in the 2040 scenario, *figure 6.13*. Low volumes are attracted to the most central nodes. Instead, most of the traffic travels towards the outer nodes in the traffic system.

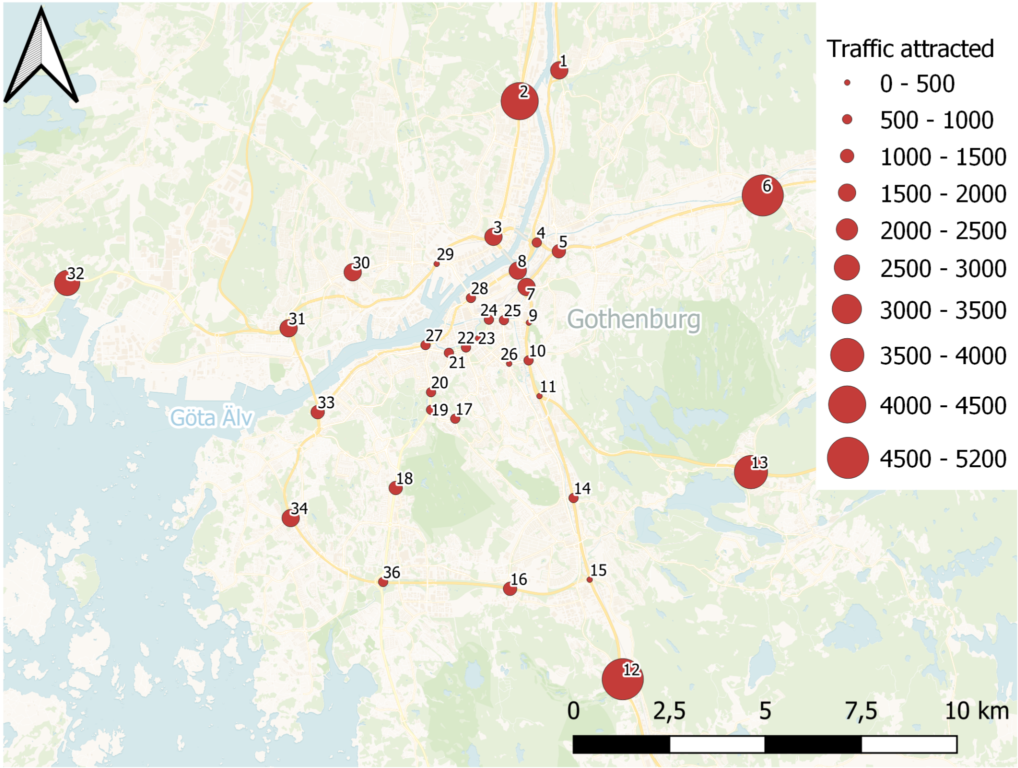


Figure 6.13: *The traffic attracted to all nodes in the traffic network 2040.*

6.5 Lane configuration 2040

Just as with the 2022 scenario the 2040 scenario requires two iterations before the same lane configuration is generated. Similarly, to the 2022 scenario the road *Ullevigatan* is deemed the optimal strategy for the RLSs, *figure 6.14*. However, in this analysis Ullevigatan is divided into two sections *a* and *b*. For the 2022 scenario the RLS is implemented in Ullevigatan b whereas in the 2040 scenario RLS is implemented in Ullevigatan a. At 674 meters this part section of Ullevigatan is slightly longer than the RLS implemented for the 2022 scenario.

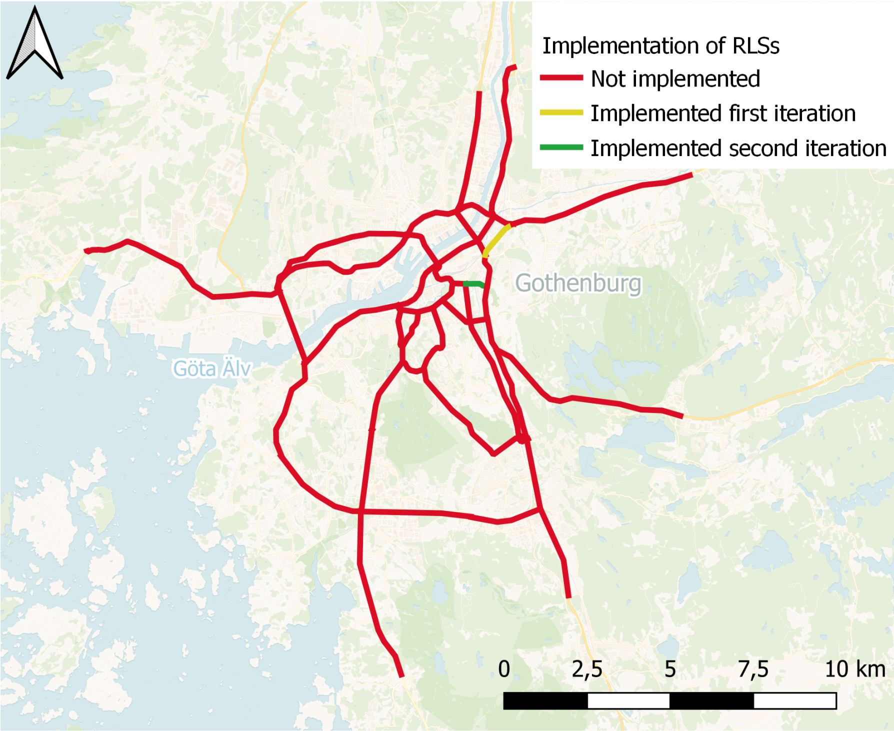


Figure 6.14: *The traffic attracted to all nodes in the traffic network 2040.*

As a result of the change in lane configuration the travel behaviour in the traffic network changes. In *table 6.2* some of the links which are heavily affected are presented. A complete table including all generated traffic volumes and the corresponding travel times are presented in *table A.8* in *Appendix A*.

Table 6.2: *The utilization rates and travel times for the links most affected by the change in lane configuration 2040.*

Link	C_0		C_2		x_0		x_2		ta_0 [min]		ta_2 [min]	
	a	a’	a	a’	a	a’	a	a’	a	a’	a	a’
5-6	78 %	64 %	74 %	64 %	4685	3832	4417	3855	4.97	4.37	4.71	4.38
7-8	85 %	109 %	84 %	101 %	4984	6359	4917	5919	0.55	1.12	0.54	0.85
7-9	75 %	81 %	75 %	78 %	5860	6291	5856	6098	0.96	1.07	0.96	1.03
9-25	64 %	41 %	48 %	40 %	1546	971	1533	643	0.87	0.81	0.82	0.81
11-13	103 %	75 %	105 %	76 %	3597	2627	3661	2646	8.23	3.79	8.87	3.80
14-17	87 %	67 %	88 %	70 %	699	535	704	563	7.25	5.81	7.34	5.93
14-26	33 %	83 %	30 %	81 %	263	622	241	648	4.48	6.25	4.48	6.02
19-20	101 %	77 %	96 %	70 %	1611	1239	1532	1112	1.36	0.70	1.13	0.63
20-27	118 %	111 %	116 %	99 %	944	888	928	788	5.32	4.09	4.92	2.74

For the 2040 scenario there are about 2500 more total traffic on links in the optimized scenario without RLSs than the optimized scenario with RLSs, *figure 6.15*. In contrast to the 2022 scenarios this is actually a significant difference.

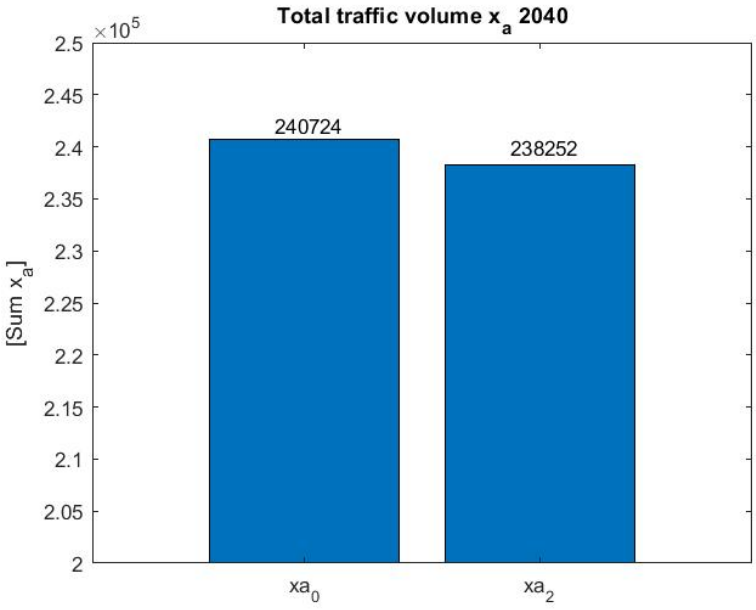


Figure 6.15: *The total number of vehicles on the roads in the traffic network 2040.*

When the measured traffic volumes are increased by a factor of 1.25 the total travel time in the system increases significantly. Without any further alterations the total system travel time amounts to 624 594 minutes every peak hour, *figure 6.16*. Though the optimized scenario without RLSs is significantly better with a total system travel time at 537 530 minutes.

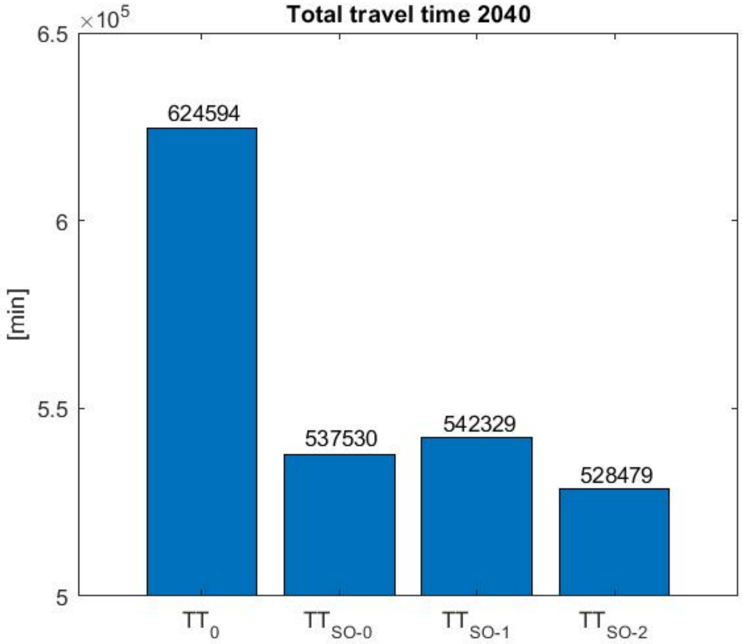


Figure 6.16: *The total system travel time for different lane configurations in the 2040 scenario.*

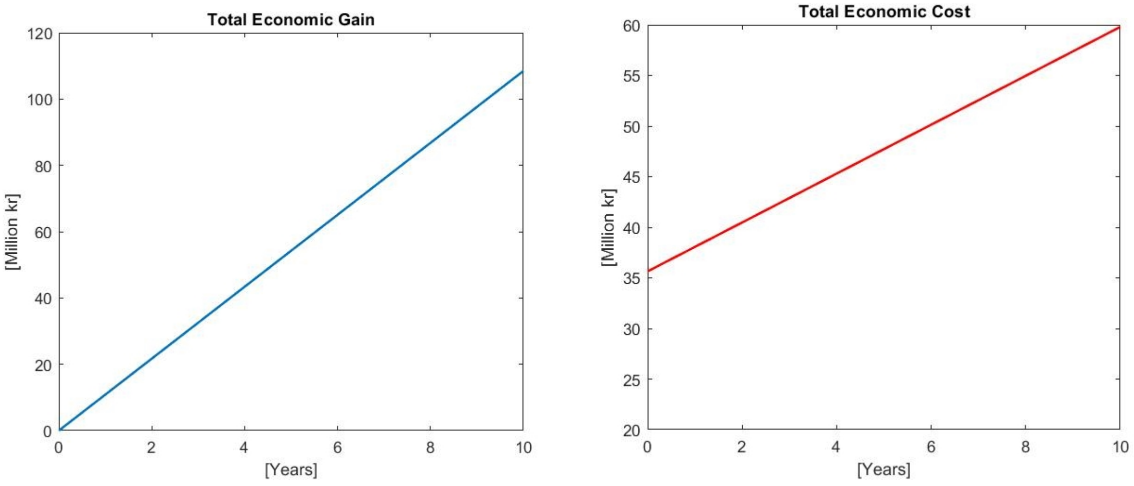
For the first iteration the algorithm does not find a lane configuration which results in a lower travel time than that. However, with a RLS applied to Ullevigatan a, which is found in the second iteration, the total system travel time decreases to 528 479 minutes.

Since the RLS is implemented over a short length only two zipper machines are required. Combined with the cost for the movable barriers the total investment cost amounts to about 35 600 000 kr, *table 6.3.* The daily operational and maintenance costs is expected to be a bit over 10 000 kr. Here the operational costs are exceeded by the generated value which amounts to 46 165 kr.

Table 6.3: *Cost estimations for constructing and operationg RLSs with movable barriers 2040.*

Type	Value	Unit
Zipper machines	30 144 000	[kr]
Movable Barrier	5 495 796	[kr]
Daily Operational cost	10 281	[kr/day]
Daily value generated	46 165	[kr/day]

As a consequence of this there is an economic upside to implementing this RLS under these traffic volumes. Over a ten-year period, this system is expected to generate a societal value of over 100 million kr, *figure 6.17a.* In contrast to the costs which is expected to amount to 60 million kr, *figure 6.17b.*



(a) *Economic gain.* **(b)** *Economic cost.*

Figure 6.17: *The expected economic gain and costs for the RLS over a ten year period for the 2040 scenario.*

This means that the system would profitable for any period longer than 4 years after the date of completion, *figure 6.18.*

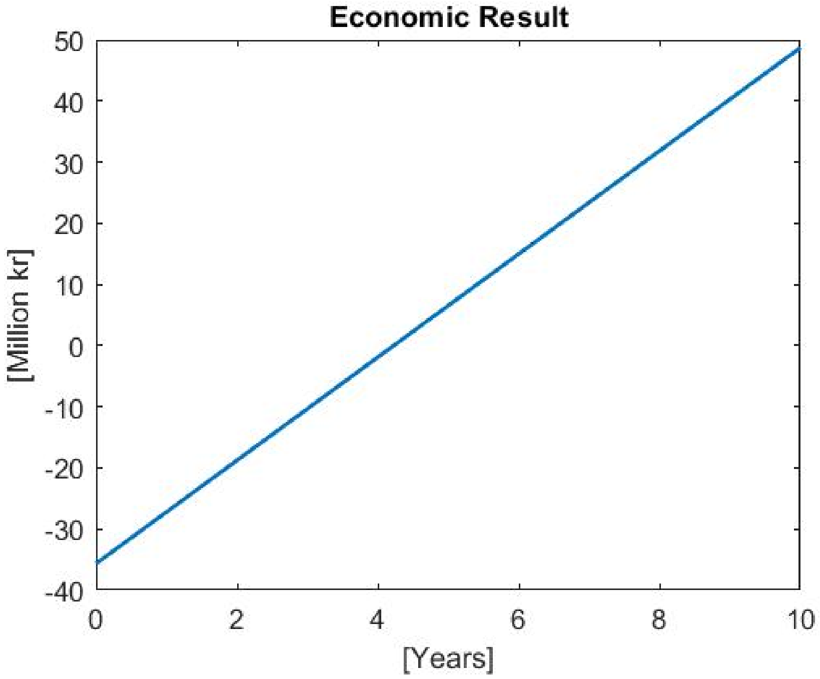


Figure 6.18: *The expected economic outcome over a ten year period for implementing RLS 2040.*

7

Discussion

The discussion is divided into two sections. In the first the viability for the RLS in Gothenburg is discussed, *section 7.1.* In the second the use of the model is deciphered, *section 7.2.*

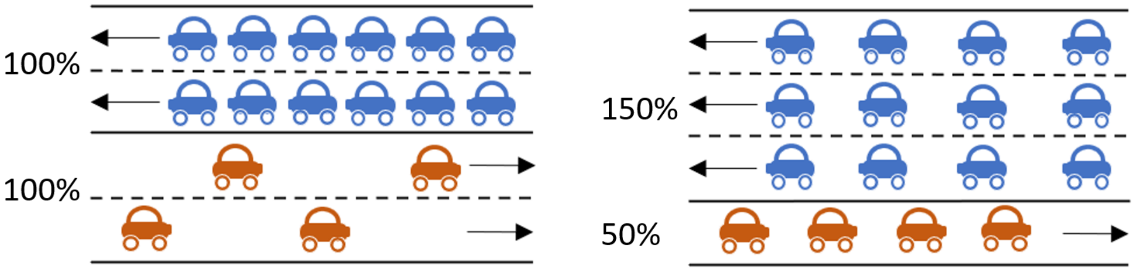
7.1 Viability RLS in Gothenburg

The simulated traffic scenarios for 2022 clearly shows that it would not be profitable to invest in RLSs in Gothenburg. While this would lower the total system travel time it does not generate enough economic value to cover the operational expenses, *figure 6.10.* Between the expenses and profits the main issue is that the generated profits are far too low. This of course is due to that the implementation of RLS is not generating a substantial decrease in total system travel time.

There are several factors which causes the RLSs to be inefficient for the traffic system in Gothenburg. One of most important is that there are few links which suffers from heavy congestion according to these calculations, *figure 6.3.* As a result, there is, in many cases, only a minor delay between the FFTTs and the peak hour travel times. Naturally, this means that there is not much time to save by implementing RLSs.

Moreover, while the traffic system of Gothenburg is affected by tidal traffic flows the effects are, in most cases, not high enough to cause large differences in the utilization rate between the two directions on the roads, *figure 6.3.* For RLSs to more effective the tidal effects would need generate heavy congestion on one side of the road while the utilization rate is below 50% in the other direction. As in seen in *figure 6.3* this is only the case for one road (Mölndalsvägen) in the 2022 scenario. Unfortunately, implementing RLSs for this road is not possible as the travel directions are separated by trams. For the other roads congestion is either not present or present in both directions.

Another factor that limits the implementation of RLSs in Gothenburg is the fact that most of the roads in the traffic network only has 2-3 lanes in each direction, *figure 6.2.* This is problematic as re-configuring so much of the total capacity is unlikely to cause a more efficient use of the space. Additionally, this issue is more significant with fewer lanes to operate. If one lane is switched on a road with two lanes in each direction the link capacity changes form 100% in both direction to 50% in one and 150% in the other, *figure 7.1.* If, for comparison, the same is done for a road with four lanes in both directions the link capacities go from 100% in both direction to 75% and 125%.



(a) *Before RLS.* **(b)** *After RLS.*

Figure 7.1: *The redistribution of capacity for a two lane road.*

There are two reasons why the latter is preferable to the former. Firstly, it is unlikely that the congestion in any direction would be severe enough so that a capacity increase of 50% is necessary. This is because the exponential increase in travel time will cause travellers to choose other paths as the traffic volume exceeds 100% since this causes heavy delays. In some cases, a 50% increase of capacity is actually very beneficial as that can cause the "redirected" traffic to once again travel on that link thus lowering the congestion on other links as well. However, this could still be the case for a link where the capacity is exceeded by 25%. Naturally, the larger the redistribution becomes the less likely it is that it is effective.

Additionally, the reduction in road capacity of 50%, for the opposite direction, is very likely to generate congestion as the utilization rate often is over 50% in both directions. This is of course less likely if only 25% of the road capacity is taken away from the link with lower traffic volume. To summarise, it is likely that the model would show that RLSs are more profitable if the traffic volumes and the number of lanes were doubled. Even though the utilization rate would be identical in the two scenarios.

Lastly the implementation of RLSs in Gothenburg is somewhat limited as there are several links where it is not feasible to implement RLSs. However, in this particular case it is not likely that it has affected the results to a significant extent as most of the links where implementation of RLSs is restricted are not exposed to high traffic volumes in these calculations, *figure 6.1 & 6.3* . The exception is Mölndalsvägen which has a large difference in utilization rates for the two directions. Though since these links only has one lane (for a significant stretch of the road) RLSs would naturally not possible anyway.

In contrast to the 2022 scenario the analysis shows that an implementation of RLSs should be profitable if the traffic volumes predicted for 2040 is realised. Naturally, the main difference between the two economical outcomes depends on the higher traffic volume present in the 2040 scenario. As seen in *section 6.5*, implementing a RLS on Ullevigatan should generate a net profit of about 50 million kr, *figure 6.18*. However, there are a couple of reasons as to why this result is probably misleading which, when taken into account, shows that the suggested investment seems better than it would be in reality.

The first reason is that the generated travel behaviours for the RLS scenario seem to be more optimized than the base scenario. That is to say that it is probable that the base scenario could be optimized even further. In turn, this means that the time gained for implementing an RLS would be lower than it seems from this analysis. One indication of this is that much of the decrease in the total system travel time is generated on links which has no direct connection to Ullevigatan, where the RLS is implemented, *table 6.2*. One of these cases is Linnegatan in the southern direction (27-20) where the average travel time is 1.35 min lower in the optimized RLS scenario compared to the optimized base scenario. This decrease in travel time represents about 10% of the total difference between the two scenarios and does not seem to be a consequence of the implementation of an RLS on Ullevigatan as there are 6 links separating the two.

Another thing that points to the base scenario being less optimized than the RLS scenario is the fact that there are fewer cars on a summation of the traffic on each individual link throughout the rush hour. Note that this does not mean that there is a difference in the number of cars driving in Gothenburg between the two scenarios as that is restricted through the algorithm constraints. However, when calculating the traffic volume on all links any vehicle can be calculated several times as it is likely that the vehicle will use several links to travel between their OD-pair. As such if a car uses 2 links to arrive at its destination it counts as two cars on the total links traffic volume while if it uses 3 links it counts as 3. Naturally it can still be preferable to use 3 links than 2 depending on the congestion, distances and speed limits on the links. Thus, this disparity, between the total link traffic volume for the base and RLS scenario, is caused by more cars taking shorter paths in the latter case. While this could partly be caused by the implementation of the RLSs it is also an indication the optimal total system travel time for the base scenario could be lower than the one found be the GA.

Another problem with the RLS is that while it manages to decrease the total system travel time it does not improve the most sever issues with congestion. As seen in *figure 6.11*, there are several links where the increase in traffic volume in the 2040 scenario has caused heavy congestion. In many of these cases the link utilisation rate exceeds that of 100%. Naturally it is vital that this level of congestion is remedied. Though as the traffic volume tend to be high in both directions of the roads in these cases RLS do not aid in reliving the congestion in the most critical parts of the traffic network.

7.2 Viability of the model

As with all analyses there are reasons as to why the results can differ from reality. For this study SO was used for simulating the travel behaviour. Whereas SO is suitable for the purpose of this study (to generate and investigate the model itself) it is somewhat limited in generating a realistic travel behaviour. As the users is likely to be more selfish in real life using UE instead is recommended if the model is used to generate decision support for actual investments.

Another one of the most important factors to highlight is the OD-matrix used for the calculations. The generated OD-matrices almost exactly generates the same traffic as the collected traffic volumes. However, unfortunately the matrices which the algorithm finds tend to be more simplistic than that which is likely to occur in reality. Particularly, the algorithm tends to find solutions where the traffic between as many OD-pairs as possible amounts to zero. Instead, there were very high traffic between a small part of the OD-pairs. In reality it is of course more probable that the travel demand is more evenly distributed between many OD-pairs in the traffic network. While restricting the model to not generate any travel demands the exceeds 250 cars improve the quality of the matrix significantly a travel demand of zero is still generated for a majority of the OD-pairs.

Another factor in which the generated OD-matrices simplifies reality, which impacts this analysis, is that the paths used generally are quite short. In other words, most paths which see use in the generated matrices connects two nodes located relatively close together. This has some major implications on the calculations which follows the generation of the OD-matrices. Firstly, since the average vehicle do not travel long distances a vast majority of the generated traffic only travels along the links with the highest traffic volume. As seen in *figure 6.4 & 6.5 & 6.12 & 6.13* this pattern is quite clear in the generated travel behaviour. As a consequence of this, the tidal effects might not be as prominent in the analysis as it is in reality. As most vehicles aim to travel to a destination close by its starting node, traffic which is generated from the most central point's tend to stay within the most central parts of the city.

While these issues with the accuracy regarding the OD-matrix is present for both the 2022- and the 2040 scenario is most pressing in the latter case. This is because the travel behaviour is expected to have further deviations from reality as the traffic volumes which the OD-matrix is calculated from is assumed rather than collected. Naturally, there is no guarantee that the traffic volumes will increase in Gothenburg over this time period. Furthermore, even if an increase of 25% were to be realised the travel behaviour (OD-matrix) is likely to be substantially different than that used in this analysis. This is because the OD-matrix used in this analysis is generated from the traffic volumes which has all been scaled up by 25%. This means that it is assumed that the increase in traffic is assumed to be on percentage equal on all links. In real life the increase would probably be far from equal since the increase in traffic is caused by further developments in the urban area, which is not evenly distributed around the city. For example, it is probable that the links on Hisingen would be exposed to a larger increase in traffic compared to most other areas of the city as the development is very concentrated in this area.

Apart from diminishing the tidal effects the problem with generating realistic travel behaviour also negatively impacts the credibility of the travel behaviour for individual vehicles. In reality it is more likely that the average trip would be longer as the tendency to travel by car increases with a longer distance. Naturally, traveling a distance lower than 1 km is unlikely to be performed using a car.

In an ideal scenario the model would be applied with a pre-existing OD-matrix. Alternatively, the OD-matrix could be generated with more traditional methods as traffic surveys. However, in many cases there does not exist an OD-matrix neither does the resources to generate one for a single traffic study. In these scenarios this method for generating an OD-matrix is sufficiently accurate for the purpose of generating an indication of whether or not RLSs would be profitable. Though the deviations from reality is sufficient as to dissuade one from basing large investments solely on the results of such an analysis.

However, there are methods to improve the accuracy of the generated OD-matrices in future analyses. One method could be to constrain the lowest average traveling distance for the cars in the traffic network. By doing so the risk for generating improbable travel behaviour where the average vehicle travels short distances is reduced. This could also mean that the tidal effects would become more prominent. Another improvement would be to vectorize the constraint which dictates that the travel demand between two OD-pairs may not exceed 250 cars. In doing so the maximum number could alternate depending on the expected traffic generated and attracted in that point.

For this particular case study, the method for implementing the model were in several regards different to the first method suggested in *section 4.1*. As previously explained, this is because of the limitations in the algorithms provided by MATLAB. Of the adjustments the most critical is the one where the model is shifted from its original bi-level structure to two separate optimization problems. It is probable that the model would still indicate that the implementation of RLSs would not be particularly effective in Gothenburg. However, there is still a chance that implementing the model with a bi-level structure would generate better solutions that the divided approach cannot find.

There are also smaller adjustments made to allow the model to comply with GA provided by MATLAB. Such as the adjustment to allow for a single exponent value rather than an exponent vector. While this is not ideal it is unlikely that it has affected the overarching result, in economic terms, in any notable extent.

Lastly the model is severely limited in the sense that it assumes that the traffic volume, economic value of the travel time and the economic value of the investment remains consistent over a long period of time. Since all of these tend to vary over time the model is most accurate when applied over shorter periods of time. However, it is rather difficult to justify large infrastructure investments when only a small time frame is taken into consideration. The model could for example be improved by implementing a traffic volume which increases incrementally over a time period. While this would not affect the investment cost directly it would affect the profitability of the RLSs as the profitability would vary between calendar years. This could also be used to model the profitability over several scenarios where the traffic increases or decreases by different levels over time.

In summation the analysis shows that this model can be used to generate an initial indication of the profitability of RLSs. While this can be performed with two different optimization problems it can negatively impact the credibility of the results. Furthermore, by using a pre-existing OD-matrix the accuracy of the model would improve greatly. Lastly, regardless of the way of implementation the model could be improved by taking the fact that traffic volumes, and the economic value of travel time, tend to vary over time.

7.3 Further studies

Regarding further studies there are a few areas to study the use of this model. As mentioned in *section 7.2* the model could be improved by taking the variability of yearly traffic into account. Additionally, varying the value of the invested and generated economic value would also be interesting. After all, 100 000kr invested today is worth much more than 100 000 generated in profit ten years later. Moreover, applying the model to larger cities, where the average amount of lanes on every road is higher, would be vital to see how the model performs in an environment more suitable to RLSs. In that case the methodology would ideally be implemented through it's intended bi-level structure. Another point of interest is defining the travel behaviour under UE instead of SO

8

Conclusions

The first conclusion of the report is that whereas RLS could become more profitable in the future it would not be profitable in Gothenburg under the current travel behaviour. The second conclusion is that while the model can be used to gain an initial indication of the profitability of RLSs it is still necessary to develop the model further before it generates sufficiently accurate results which can be used as decision support for large infrastructural investments.

References

Ab Wahab, M. N., Nefti-Meziani, S., & Atyabi, A. (2015). A comprehensive review of swarm optimization algorithms. *PloS one*, *10*(5). https://doi.org/https://doi.org/10.1371/journal.pone.0122827

AutoNavi Software Co., Ltd. (n.d.).

Barth, M., & Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record*, *2058*(1), 163–171. https://doi.org/10.3141/2058-20

CARTO. (2022). *Carto: Location intelligence & gis for cloud natives*. https://carto.com/

Conceição, L., de Almeida Correia, G. H., & Tavares, J. P. (2020). The reversible lane network design problem (rl-ndp) for smart cities with automated traffic. *Sustainability*, *12*(3), 1226. https://doi.org/10.3390/su12031226

Daganzo, C. F., & Sheffi, Y. (1977). On stochastic models of traffic assignment. *Transportation science*, *11*(3), 253–274. https://doi.org/https://web.p.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=8ff3758c-e648-4614-ac10-d0bea59faeb6\%40redis

Di, Z., & Yang, L. (2020). Reversible lane network design for maximizing the coupling measure between demand structure and network structure. *Transportation Research Part E: Logistics and Transportation Review*, *141*, 102021. https://doi.org/https://doi.org/10.1016/j.tre.2020.102021

Fisk, C. (1980). Some developments in equilibrium traffic assignment. *Proceedings of the 30th Chinese Control Conference*, *14*(3), 243–255.

Golden Gate Bridge, Highway and Transportation District. (n.d.). *Traffic management*. https://www.goldengate.org/bridge/bridge-operations/traffic-management/

Google. (2022). *Göteborg*. https://www.google.com/maps/place/G%5C%C3%5C%B6teborg/@57.7028152,11.9479304,13z/data=!4m5!3m4!1s0x464f8e67966c073f:0x4019078290e7c40!8m2!3d57.70887!4d11.97456

Göteborgs Stad. (n.d.-a). *Ansvar för vägnätet i göteborg*. https://goteborg.se/wps/portal/start/gator-vagar-och-torg/gator-och-vagar/ansvar-for-vagntet-i-goteborg

Göteborgs Stad. (n.d.-b). *Trafikmängder på olika gator*. https://goteborg.se/wps/portal/start/gator-vagar-och-torg/gator-och-vagar/statistik-om-trafiken/trafikmangder-pa-olika

Göteborgs Stad. (2011). *Trafik- och resandeutveckling 2010*. http://www2.trafikkontoret.goteborg.se/resourcelibrary/Meddelande1_11Resandeutveckling2010.pdf

Göteborgs Stad. (2013). *Trafikstrategi för göteborg - underlagsrapport: Hur många reser i göteborg 2035?* Göteborgs stad. https://goteborg.se/wps/wcm/connect/68647273-63a1-4c4f-ad24-5306e041b6a1/Underlagsrapport_Hur+m%5C%C3%5C%A5nga+reser+2035_dec13.pdf?MOD=AJPERES

Göteborgs Stad. (2018). *Trafik- och resandeutveckling 2018*. Göteborgs Stad. https://goteborg.se/wps/wcm/connect/dae0456a-8577-4d32-a131-bb6eba401cd7/TRU_2018.pdf?MOD=AJPERES

Hedman, F., & Laaksonen, A. (1999). Large scale parallel molecular dynamics simulations. *Theoretical and Computational Chemistry*, *7*, 231–280. https://doi.org/https://doi.org/10.1016/S1380-7323(99)80040-5

INRIX. (2019). *Inrix: Congestion costs each american 97 hours, $1,348 a year*. https://inrix.com/press-releases/scorecard-2018-us/

Karoonsoontawong, A., & Lin, D.-Y. (2011). Time-varying lane-based capacity reversibility for traffic management. *Computer-Aided Civil and Infrastructure Engineering*, *26*(8), 632–646.

Kokash, N. (2005). An introduction to heuristic algorithms. *Department of Informatics and Telecommunications*, 1–8. https://doi.org/https://doi.org/10.1016/S1380-7323(99)80040-5

KTH. (2021). *Efficient od estimation*. https://www.kth.se/ctr/research/completed-projects/efficient-od-estimation-1.741889

Kungliga Tekniska Högskolan. (2009). *Algoritmer*. https://www.csc.kth.se/utbildning/kth/kurser/DD1341/inda10/algorithms/algoritmer/

Li, Q., & Gao, Z. (2014). Managing rush hour congestion with lane reversal and tradable credits. *Mathematical Problems in Engineering*, *2014*. https://doi.org/http://dx.doi.org/10.1155/2014/132936

Liang, X., Hu, C., Ma, C., & Mao, B. (2011). Empirical study on variable lanes design of chaoyang north street in beijing. *Proceedings of the 30th Chinese Control Conference*, 5527–5531.

Lindsay Transportation Solutions. (2019). *The road zipper system: Moving people. safer. faster. smarter ... better*. https://www.lindsay.com/uploads/files/sections/320-road_zipper_brochure_08_06_2019.pdf

Liu, Y., & Wu, H. (2017). Prediction of road traffic congestion based on random forest. *Asian conference on intelligent information and database systems*, *2*, 361–364. https://doi.org/10.1109/ISCID.2017.216

Lu, T., Yang, Z., Ma, D., & Jin, S. (2018). Bi-level programming model for dynamic reversible lane assignment. *IEEE Access*, *6*, 71592–71601.

Mannering, F., Garrison, D. H., & Sebranke, B. (1990). *Generation and assessment of incident management strategies, volume iv: Seattle area incident impact analysis: Microcomputer traffic simulation results*. University of Washington https://www.wsdot.wa.gov/research/reports/fullreports/204.4.pdf.

Mannering, F. L., & Washburn, S. S. (2013). *Principles of highway engineering and traffic analysis* (Vol. 5). John Wiley & Sons Inc.

MathWorks, Inc. (2022a). *Global optimization toolbox*. https://se.mathworks.com/help/gads/

MathWorks, Inc. (2022b). *How the genetic algorithm works.* https://se.mathworks.com/help/gads/how-the-genetic-algorithm-works.html

MathWorks, Inc. (2022c). *Optimization toolbox.* https://se.mathworks.com/help/optim/

Meng, Q., Khoo, H. L., & Cheu, R. L. (2008). Microscopic traffic simulation model-based optimization approach for the contraflow lane configuration problem. *Journal of Transportation Engineering*, *134*(1), 41–49. https://doi.org/10.1061/(ASCE0733)-947X(2008)134:1(41)

Mo, J., Gao, M., & Liu, L. (2019). An improved critical-edge model for finding optimal contraflow links considering the influence of intersections. *Mathematical Problems in Engineering*, *2019*. https://doi.org/https://doi.org/10.1155/2019/8681417

Pham, D., & Karaboga, D. (2012). *Intelligent optimisation techniques: Genetic algorithms, tabu search, simulated annealing and neural networks.* Springer Science & Business Media.

Port of Gothenburg. (n.d.). *The port of gothenburg.* https://www.portofgothenburg.com/about-the-port/the-port-of-gothenburg/

Qgis. (2022). *Qgis: A free and open source geographic information system.* https://qgis.org/en/site/

Rathbone, D. B. (2017). *Improving the cost-effectiveness of urban freeways: Through flexibility in operations and design.* https://www.lindsay.com/uploads/files/resources/472-improving_the_cost_effectiveness_of_urban_freeways_dbr_12202017.pdf

Rodrigue, J.-P., & Ducruet, C. (2020). *2.1 – the geography of transportation networks.* https://transportgeography.org/contents/chapter2/geography-of-transportation-networks/

Tang, Q., & Hu, X. (2019). *Triggering behavior changes with information and incentives: An active traffic and demand management-oriented review* (Vol. 3). Elsevier.

Trafikverket. (n.d.-a). *Nvdb på webb.* https://bit.ly/3y9xWC5

Trafikverket. (n.d.-b). *Välkomen till trafikflödeskartan.* https://vtf.trafikverket.se/SeTrafikinformation

Trafikverket. (2013). *Trvmb kapacitet och framkomlighetseffekter: Trafikverkets metodbeskrivning för beräkning av kapacitet och framkomlighetseffekter i vägtrafikanläggningar.* https://docplayer.se/10681438-Trvmb-kapacitet-och-framkomlighetseffekter.html

Trafikverket. (2020). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: Asek 7.0 kapitel 8 kostnad för trängsel och förseningar.* https://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-2021/08_trangsel_forseningar_a7.pdf

Trafikverket, & Göteborgs Stad. (2019). *Alternativa trafikprognosscenarier för storgöteborg.* https://www4.goteborg.se/prod/Intraservice/Namndhandlingar/SamrumPortal.nsf/EC0F765548C00C50C12585CA004630E4/$File/Bilaga%203.pdf?OpenElement

Tuydes, H., & Ziliaskopoulos, A. (2006). Tabu-based heuristic approach for optimization of network evacuation contraflow. *Transportation Research Record*, *1964*(1), 157–168.

UN. (2018). *68% of the world population projected to live in urban areas by 2050, says un.* https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

University of Gothenburg. (2022). *Gothenburg.* https://www.gu.se/en/about-the-university/welcome-services/gothenburg

U.S. Department of Transportation. (2017). *Simplified highway capacity calculation method for the highway performance monitoring system.* Federal Highway Administration. https://www.fhwa.dot.gov/policyinformation/pubs/pl18003/hpms_cap.pdf

Västsvenska Industri- och Handelskammaren. (2010). *Reversibla körfält i göteborgsområdet: En teknik för framtiden.* Västsvenska Industri- och Handelskammaren. https://docplayer.se/6804481-Reversibla-korfalt-i-goteborgsomradet-en-teknik-for-framtiden.html

Washington State Department of Transportation. (n.d.). *Express lanes.* https://wsdot.wa.gov/travel/roads-bridges/express-lanes

Weisbrod, G., Vary, D., & Treyz, G. (2003). Measuring economic costs of urban traffic congestion to business. *Transportation research record*, *1839*(1), 98–106.

Wilson, R. (1972). *Triggering behavior changes with information and incentives: An active traffic and demand management-oriented review* (Vol. 4). Longman Group Ltd.

Wolshon, B., & Lambert, L. (2006). Reversible lane systems: Synthesis of practice. *Journal of Transportation Engineering*, *132*(12), 933–944. https://doi.org/10.1061/(ASCE)0733-947X(2006)132:12(933)

World Highways. (2018). *Lindsay argues the case for reversible lanes over adding lanes.* https://www.worldhighways.com/wh11/feature/lindsay-argues-case-reversible-lanes-over-adding-lanes

Wu, J., Sun, H., Gao, Z., & Zhang, H. (2009). Reversible lane-based traffic network optimization with an advanced traveller information system. *Transportmetrica B: Transport Dynamics*, *41*(1), 87–97. https://doi.org/https://www.tandfonline.com/action/showCitFormats?doi=10.1080/03052150802368799

Xie, C., Lin, D.-Y., & Waller, S. T. (2010). A dynamic evacuation network optimization problem with lane reversal and crossing elimination strategies. *Transportation research part E: logistics and transportation review*, *46*(3), 295–316.

Ximeng, C. (2013). *Reversible lanes put into effect in beijing.* https://www.globaltimes.cn/content/810920.shtml

Yang, H., & Bell, M. G. H. (1998). Models and algorithms for road network design: A review and some new developments. *Transport Reviews*, *18*(3), 257–278. https://doi.org/https://doi.org/10.1080/01441649808717016

You, R., Chen, W.-N., Gong, Y.-J., Lin, Y., & Zhang, J. (2019). A histogram estimation of distribution algorithm for reversible lanes optimization problems.

2019 IEEE Congress on Evolutionary Computation (CEC), 1960–1966. https://doi.org/978-1-7281-2153-6/19/\$31.00

Zhang, H., & Gao, Z. (2007). Two-way road network design problem with variable lanes. *Journal of Systems Science and Systems Engineering*, *16*(1), 50–61. https://doi.org/10.1007/s11518-007-5034-x

Zhao, J., Ma, W., Liu, Y., & Yang, X. (2014). Integrated design and operation of urban arterials with reversible lanes. *Transportmetrica B: Transport Dynamics*, *2*(2), 130–150. https://doi.org/http://dx.doi.org/10.1080/21680566.2014.908751

Zhou, W. W., Livolsi, P., Miska, E., Zhang, H., Wu, J., & Yang, D. (1993). An intelligent traffic responsive contraflow lane control system. *Proceedings of VNIS'93-Vehicle Navigation and Information Systems Conference*, 174–181.

Ziliaskopoulos, A. K. (2000). A linear programming model for the single destination system optimum dynamic traffic assignment problem. *Transportation science*, *34*(1), 37–49. https://doi.org/0041-1655/00/3401-0037

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Appendix A

Table A.1: *Collected and calculated data regarding the Gothenburg traffic system.*

Link number	Link OD	Name	v_0	l_a	t_0	dir	z
1	1-4	Marieholmsleden	80	4674	3.51	M	1
2	2-3	Kungälvsleden	80	3614	2.71	M	1
3	3-4	Marieholmstunneln	70	1200	1.03	M	0
4	3-8	Tingstadstunneln	50	1022	1.23	M	0
5	3-29	Lundbyleden$_a$	70	1768	1.52	F	1
6	4-5	Partihallsförbindelsen	70	682	0.58	F	1
7	4-8	E45$_a$	70	868	0.74	M	0
8	5-6	Alingsåsleden$_a$	80	5532	4.15	F	1
9	5-7	Alingsåsleden$_b$	80	1265	1.08	M	1
10	7-8	E6$_a$	70	477	0.41	F	0
11	7-9	E6$_b$	70	970	0.83	M	1
12	8-28	E45$_b$	70	1431	1.23	M	0
13	9-10	E6$_c$	70	991	0.85	F	1
14	9-25	Ullevigatan$_a$	50	674	0.81	M	1
15	10-11	E6$_d$	70	664	0.57	F	0
16	10-26	Örgrytevägen	50	505	0.61	M	0
17	11-13	R40	100	5896	3.54	F	1
18	11-14	E6$_e$	80	2850	2.14	F	1
19	12-15	E6$_g$	80	2754	2.07	M	1
20	14-15	E6$_f$	80	2108	1.58	F	1
21	14-17	Toltorps-/Bifrostgatan	50	4587	5.50	M	0
22	14-26	Mölndalsvägen	50	3733	4.48	M	0
23	15-16	Söderleden$_a$	80	2232	1.67	M	1
24	16-36	Söderleden$_b$	80	3212	2.41	M	1
25	17-19	Per Dubbsgatan	50	779	0.93	F	0
26	17-22	Aschebergsgatan	50	2211	2.65	M	0
27	18-19	Dag Hammarskjöldsleden$_a$	60	2277	2.28	M	1
28	18-36	Dag Hammarskjöldsleden$_b$	80	2457	1.84	F	1
29	19-20	Dag Hammarskjöldsleden$_c$	50	463	0.56	M	1
30	20-21	Övre Husarsgatan	50	1153	1.38	M	1
31	20-27	Linnégatan	50	1343	1.61	F	0

Continued on next page

Table A.1 – continued from previous page

Link number	Link OD	Name	v_0	l_a	t_0	dir	z
32	21-22	Parkgatan$_a$	50	486	0.58	M	0
33	21-27	Norra Allegatan	50	683	0.82	F	0
34	22-23	Parkgatan$_b$	50	375	0.45	M	0
35	23-24	Parkgatan$_c$	50	636	0.76	F	0
36	23-26	Södra Vägen	50	1104	1.32	F	0
37	24-25	Ullevigatan$_b$	50	412	0.49	F	1
38	24-28	Burggrevegatan	50	1088	1.31	F	0
39	25-26	Skånegatan	50	1142	1.37	F	0
40	27-28	E45$_c$	50	1841	2.21	M	0
41	27-33	Oscarsleden	70	3455	2.96	F	1
42	28-29	Nya Hisingsbron	50	1384	1.66	F	0
43	29-30	Hjalmarbrantingsgatan$_a$	50	2221	2.67	F	0
44	29-31	Lundbyleden$_b$	70	4831	4.14	F	0
45	30-31	Hjalmarbrantingsgatan$_b$	60	2512	2.51	F	0
46	31-32	R155	80	6404	4.80	F	1
47	31-33	Älvsborgsbron	70	2269	1.94	M	1
48	33-34	Västerleden$_a$	70	3111	2.67	F	0
49	34-36	Västerleden$_b$	70	3025	2.59	M	1
50	35-36	R158	70	5180	4.44	F	1
51	4-1	Marieholmsleden	80	4674	3.51	F	1
52	3-2	Kungälvsleden	80	3614	2.71	F	1
53	4-3	Marieholmstunneln	70	1200	1.03	F	0
54	8-3	Tingstadstunneln	50	1022	1.23	F	0
55	29-3	Lundbyleden$_a$	70	1768	1.52	M	1
56	5-4	Partihallsförbindelsen	70	682	0.58	M	1
57	8-4	E45$_a$	70	868	0.74	F	0
58	6-5	Alingsåsleden$_a$	80	5532	4.15	M	1
59	7-5	Alingsåsleden$_b$	80	1265	1.08	F	1
60	8-7	E6$_a$	70	477	0.41	M	0
61	9-7	E6$_b$	70	970	0.83	F	1
62	28-8	E45$_b$	70	1431	1.23	F	0
63	10-9	E6$_c$	70	991	0.85	M	1
64	25-9	Ullevigatan$_a$	50	674	0.81	F	1
65	11-10	E6$_d$	70	664	0.57	M	0
66	26-10	Örgrytevägen	50	505	0.61	F	0
67	13-11	R40	100	5896	3.54	M	1
68	14-11	E6$_e$	80	2850	2.14	M	1
69	15-12	E6$_g$	80	2754	2.07	F	1
70	15-14	E6$_f$	80	2108	1.58	M	1
71	17-14	Toltorps-/Bifrostgatan	50	4587	5.50	F	0
72	26-14	Mölndalsvägen	50	3733	4.48	F	0
73	16-15	Söderleden$_a$	80	2232	1.67	F	1
74	36-16	Söderleden$_b$	80	3212	2.41	F	1
75	19-17	Per Dubbsgatan	50	779	0.93	M	0

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Table A.1 – continued from previous page

Link number	Link OD	Name	v_0	l_a	t_0	dir	z
76	22-17	Aschebergsgatan	50	2211	2.65	F	0
77	19-18	Dag Hammarskjöldsleden$_a$	60	2277	2.28	F	1
78	36-18	Dag Hammarskjöldsleden$_b$	80	2457	1.84	M	1
79	20-19	Dag Hammarskjöldsleden$_c$	50	463	0.56	F	1
80	21-20	Övre Husarsgatan	50	1153	1.38	F	1
81	27-20	Linnégatan	50	1343	1.61	M	0
82	22-21	Parkgatan$_a$	50	486	0.58	F	0
83	27-21	Norra Allegatan	50	683	0.82	M	0
84	23-22	Parkgatan$_b$	50	375	0.45	F	0
85	24-23	Parkgatan$_c$	50	636	0.76	M	0
86	26-23	Södra Vägen	50	1104	1.32	M	0
87	25-24	Ullevigatan$_b$	50	412	0.49	M	1
88	28-24	Burggrevegatan	50	1088	1.31	M	0
89	26-25	Skånegatan	50	1142	1.37	M	0
90	28-27	E45$_c$	50	1841	2.21	F	0
91	33-27	Oscarsleden	70	3455	2.96	M	1
92	29-28	Nya Hisingsbron	50	1384	1.66	M	0
93	30-29	Hjalmarbrantingsgatan$_a$	50	2221	2.67	M	0
94	31-29	Lundbyleden$_b$	70	4831	4.14	M	0
95	31-30	Hjalmarbrantingsgatan$_b$	60	2512	2.51	M	0
96	32-31	R155	80	6404	4.80	M	1
97	33-31	Älvsborgsbron	70	2269	1.94	F	1
98	34-33	Västerleden$_a$	70	3111	2.67	M	0
99	36-34	Västerleden$_b$	70	3025	2.59	F	1
100	36-35	R158	70	5180	4.44	M	1

Table A.2: *Collected and calculated data regarding the Gothenburg traffic system (SI: Signalised intersection).*

Link	Link OD	Access	SI	Lanes	Inclination [%]	v_0	Road type
1	1-4	No	No	2	2-3	80	Urban Highway
2	2-3	Yes	No	3	<2	80	Freeway
3	3-4	Yes	No	3	2-3	70	Freeway
4	3-8	Yes	No	3	2-3	50	Freeway
5	3-29	Yes	No	2	>4	70	Freeway
6	4-5	Yes	No	2	>4	70	Freeway
7	4-8	Yes	No	3	<2	70	Freeway
8	5-6	Yes	No	3	<2	80	Freeway
9	5-7	Yes	No	3	<2	70	Freeway
10	7-8	Yes	No	3	<2	70	Freeway
11	7-9	Yes	No	4	<2	70	Freeway
12	8-28	No	No	3	<2	70	Urban Highway
13	9-10	Yes	No	3	<2	70	Freeway
14	9-25	No	Yes	3		50	Signalised

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Table A.2 – continued from previous page

Link	Link OD	Access	SI	Lanes	Inclination[%]	v_0	Road type
15	10-11	Yes	No	3	2-3	70	Freeway
16	10-26	No	Yes	2		50	Signalised
17	11-13	Yes	No	2	>4	100	Urban Highway
18	11-14	Yes	No	3	<2	80	Freeway
19	12-15	Yes	No	4	<2	80	Freeway
20	14-15	Yes	No	3	<2	80	Freeway
21	14-17	No	Yes	1		50	Signalised
22	14-26	No	Yes	2		50	Signalised
23	15-16	Yes	No	3	<2	80	Signalised
24	16-36	Yes	No	2	<2	80	Freeway
25	17-19	No	Yes	2		50	Signalised
26	17-22	No	Yes	1		50	Signalised
27	18-19	No	No	2	<2	60	Multilane Highway
28	18-36	No	No	2	<2	80	Urban Highway
29	19-20	No	Yes	2		50	Signalised
30	20-21	No	Yes	1		50	Signalised
31	20-27	No	Yes	1		50	Signalised
32	21-22	No	Yes	3		50	Signalised
33	21-27	No	Yes	2		50	Signalised
34	22-23	No	Yes	3		50	Signalised
35	23-24	No	Yes	2		50	Signalised
36	23-26	No	Yes	1		50	Signalised
37	24-25	No	Yes	2		50	Signalised
38	24-28	No	Yes	2		50	Signalised
39	25-26	No	Yes	2		50	Signalised
40	27-28	Yes	No	3	2-3	50	Freeway
41	27-33	Yes	No	2	3-4	70	Freeway
42	28-29	No	No	2	2-3	50	Multilane Highway
43	29-30	No	Yes	2		50	Signalised
44	29-31	No	No	3	3-4	70	Urban Highway
45	30-31	No	Yes	2		60	Signalised
46	31-32	No	No	3	3-4	80	Urban Highway
47	31-33	Yes	No	3	3-4	70	Multilane Highway
48	33-34	Yes	No	2	<2	70	Freeway
49	34-36	No	No	3	<2	70	Urban Highway
50	35-36	No	No	3	<2	70	Urban Highway
51	4-1	No	No	2	2-3	80	Urban Highway
52	3-2	Yes	No	3	<2	80	Freeway
53	4-3	Yes	No	3	2-3	70	Freeway
54	8-3	Yes	No	3	2-3	50	Freeway
55	29-3	Yes	No	2	>4	70	Freeway
56	5-4	Yes	No	2	>4	70	Freeway
57	8-4	Yes	No	3	<2	70	Freeway
58	6-5	Yes	No	3	<2	80	Freeway

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Table A.2 – continued from previous page

Link	Link OD	Access	SI	Lanes	Inclination[%]	v_0	Road type
59	7-5	Yes	No	3	<2	70	Freeway
60	8-7	Yes	No	3	<2	70	Freeway
61	9-7	Yes	No	4	<2	70	Freeway
62	28-8	No	No	3	<2	70	Urban Highway
63	10-9	Yes	No	3	<2	70	Freeway
64	25-9	No	Yes	3		50	Signalised
65	11-10	Yes	No	3	2-3	70	Freeway
66	26-10	No	Yes	2		50	Signalised
67	13-11	Yes	No	2	<2	100	Urban Highway
68	14-11	Yes	No	3	<2	80	Freeway
69	15-12	Yes	No	4	<2	80	Freeway
70	15-14	Yes	No	3	<2	80	Freeway
71	17-14	No	Yes	1		50	Signalised
72	26-14	No	Yes	2		50	Signalised
73	16-15	Yes	No	3	<2	80	Signalised
74	36-16	Yes	No	2	<2	80	Freeway
75	19-17	No	Yes	2		50	Signalised
76	22-17	No	Yes	1		50	Signalised
77	19-18	No	No	2	<2	60	Multilane Highway
78	36-18	No	No	2	<2	80	Urban Highway
79	20-19	No	Yes	2		50	Signalised
80	21-20	No	Yes	1		50	Signalised
81	27-20	No	Yes	1		50	Signalised
82	22-21	No	Yes	3		50	Signalised
83	27-21	No	Yes	2		50	Signalised
84	23-22	No	Yes	3		50	Signalised
85	24-23	No	Yes	2		50	Signalised
86	26-23	No	Yes	1		50	Signalised
87	25-24	No	Yes	2		50	Signalised
88	28-24	No	Yes	2		50	Signalised
89	26-25	No	Yes	2		50	Signalised
90	28-27	Yes	No	3	2-3	50	Freeway
91	33-27	Yes	No	2	3-4	70	Freeway
92	29-28	No	No	2	2-3	50	Multilane Highway
93	30-29	No	Yes	2		50	Signalised
94	31-29	No	No	3	3-4	70	Urban Highway
95	31-30	No	Yes	2		60	Signalised
96	32-31	No	No	3	3-4	80	Urban Highway
97	33-31	Yes	No	3	3-4	70	Multilane Highway
98	34-33	Yes	No	2	<2	70	Freeway
99	36-34	No	No	3	3-4	70	Urban Highway
100	36-35	No	No	3	<2	70	Urban Highway

Table A.3: *The original and adjusted α&β values.*

Link number	Link OD	α_0	α_1	β_0	β_1
4	3-8	1.1465	4.4239	1.3784	6.5856
14	9-25	1.1465	4.4239	1.3784	6.5856
16	10-26	1.1465	4.4239	1.3784	6.5856
17	11-13	1.1491	6.8677	1.1218	6.5856
20	14-17	0.6846	5.1644	0.77294	6.5856
21	14-26	0.6846	5.1644	1.3784	6.5856
25	17-19	1.1465	4.4239	1.3784	6.5856
26	17-22	0.6846	5.1644	0.77294	6.5856
27	18-19	1.03	5.5226	1.1275	6.5856
29	19-20	1.1465	4.4239	1.3784	6.5856
30	20-21	0.6846	5.1644	0.77294	6.5856
31	20-27	0.6846	5.1644	0.77294	6.5856
32	21-22	1.1465	4.4239	1.3784	6.5856
33	21-27	1.1465	4.4239	1.3784	6.5856
34	22-23	1.1465	4.4239	1.3784	6.5856
35	23-24	1.1465	4.4239	1.3784	6.5856
36	23-26	0.6846	5.1644	0.77294	6.5856
37	24-25	1.1465	4.4239	1.3784	6.5856
38	24-28	1.1465	4.4239	1.3784	6.5856
39	25-26	1.1465	4.4239	1.3784	6.5856
40	27-28	1.1465	4.4239	1.3784	6.5856
42	28-29	1.1465	4.4239	1.3784	6.5856
43	29-30	1.1465	4.4238	1.3784	6.5856
45	30-31	1.03	5.5226	1.1275	6.5856
54	8-3	1.1465	4.4239	1.3784	6.5856
64	25-9	1.1465	4.4239	1.3784	6.5856
66	26-10	1.1465	4.4239	1.3784	6.5856
67	13-11	1.1491	6.8677	1.1218	6.5856
70	17-14	0.6846	5.1644	0.77294	6.5856
71	26-14	0.6846	5.1644	1.3784	6.5856
75	19-17	1.1465	4.4239	1.3784	6.5856
76	22-17	0.6846	5.1644	0.77294	6.5856
77	19-18	1.03	5.5226	1.1275	6.5856
79	20-19	1.1465	4.4239	1.3784	6.5856
80	21-20	0.6846	5.1644	0.77294	6.5856
81	27-20	0.6846	5.1644	0.77294	6.5856
82	22-21	1.1465	4.4239	1.3784	6.5856
83	27-21	1.1465	4.4239	1.3784	6.5856
84	23-22	1.1465	4.4239	1.3784	6.5856
85	24-23	1.1465	4.4239	1.3784	6.5856
86	26-23	0.6846	5.1644	0.77294	6.5856
87	25-24	1.1465	4.4239	1.3784	6.5856
88	28-24	1.1465	4.4239	1.3784	6.5856
89	26-25	1.1465	4.4239	1.3784	6.5856

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Table A.3 – continued from previous page

Link number	Link OD	α_0	α_1	β_0	β_1
90	28-27	1.1465	4.4239	1.3784	6.5856
92	29-28	1.1465	4.4239	1.3784	6.5856
93	30-29	1.1465	4.4238	1.3784	6.5856
95	31-30	1.03	5.5226	1.1275	6.5856

Table A.4: *The collected traffic volume and calculated Capacity and Utilisation rate rates of the links in the traffic network.*

Link number	Link OD	Peak traffic volume	Road capacity	Utilization rate
1	1-4	1617	3900	41 %
2	2-3	2041	5850	35 %
3	3-4	1717	5850	29 %
4	3-8	3850	5400	71 %
5	3-29	1630	3900	42 %
6	4-5	1193	3900	31 %
7	4-8	2490	5700	44 %
8	5-6	4486	6000	75 %
9	5-7	3080	5850	53 %
10	7-8	5134	5850	88 %
11	7-9	3901	7800	50 %
12	8-28	2208	5100	43 %
13	9-10	3852	5700	68 %
14	9-25	990	2400	41 %
15	10-11	4107	5700	72 %
16	10-26	710	1600	44 %
17	11-13	2945	3500	84 %
18	11-14	2841	6000	47 %
19	12-15	2174	8000	27 %
20	14-15	2740	6000	46 %
21	14-17	710	800	89 %
22	14-26	610	800	76 %
23	15-16	2875	6000	48 %
24	16-36	3573	4100	87 %
25	17-19	1020	1600	64 %
26	17-22	460	800	58 %
27	18-19	1080	3300	33 %
28	18-36	1760	3900	45 %
29	19-20	1090	1600	68 %
30	20-21	570	800	71 %
31	20-27	330	800	41 %
32	21-22	870	2400	36 %
33	21-27	180	1600	11 %
34	22-23	970	2400	40 %
35	23-24	980	1600	61 %

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Table A.4 – continued from previous page

Link number	Link OD	Peak traffic volume	Road capacity	Utilization rate
36	23-26	230	800	29 %
37	24-25	1000	1600	63 %
38	24-28	1010	1600	63 %
39	25-26	660	1600	41 %
40	27-28	2061	5550	37 %
41	27-33	1672	3900	43 %
42	28-29	1150	2800	41 %
43	29-30	940	1600	59 %
44	29-31	1912	3400	56 %
45	30-31	1250	1800	69 %
46	31-32	1850	4650	40 %
47	31-33	2129	4800	44 %
48	33-34	3337	3900	86 %
49	34-36	3381	5100	66 %
50	35-36	951	5100	19 %
51	4-1	1472	3900	38 %
52	3-2	3642	5850	62 %
53	8-3	1909	5850	33 %
54	8-3	4110	5550	74 %
55	29-3	2280	3800	60 %
56	5-4	1048	3900	27 %
57	8-4	2768	5700	49 %
58	6-5	3086	6000	51 %
59	7-5	4178	5850	71 %
60	8-7	5174	5850	88 %
61	9-7	5235	7600	69 %
62	28-8	3118	5100	61 %
63	10-9	3994	5700	70 %
64	25-9	1200	2400	50 %
65	11-10	4062	5700	71 %
66	26-10	1050	1600	66 %
67	13-11	2111	4000	53 %
68	14-11	2087	6000	35 %
69	15-12	4389	7800	56 %
70	15-14	2905	6000	48 %
71	17-14	480	800	60 %
72	26-14	380	800	48 %
73	16-15	3188	6000	53 %
74	36-16	3614	4000	90 %
75	19-17	1180	1600	74 %
76	22-17	460	800	58 %
77	19-18	1150	3300	35 %
78	36-18	1770	3900	45 %
79	20-19	910	1600	57 %

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Table A.4 – continued from previous page

Link number	Link OD	Peak traffic volume	Road capacity	Utilization rate
80	21-20	560	800	70 %
81	27-20	410	800	51 %
82	22-21	760	2400	32 %
83	27-21	600	1600	38 %
84	23-22	810	2400	34 %
85	24-23	670	1600	42 %
86	26-23	230	800	29 %
87	25-24	560	1600	35 %
88	28-24	1300	1600	81 %
89	26-25	620	1600	39 %
90	28-27	2291	5550	41 %
91	33-27	1461	3900	37 %
92	29-28	1490	2800	53 %
93	30-29	920	1600	58 %
94	31-29	1262	3400	37 %
95	31-30	880	1800	49 %
96	32-31	2110	4650	45 %
97	33-31	2727	4800	57 %
98	34-33	2494	3900	64 %
99	36-34	3217	4800	67 %
100	36-35	2432	5100	48 %

Table A.5: *The resulting OD-matrix for 2022.*

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	250	248	0	174	12	49	43	28	0	0	0	0	0	2	0	0	0
2	250	0	138	249	0	225	247	215	250	0	0	136	191	0	87	121	16	0
3	43	0	0	250	0	106	225	18	0	0	0	203	0	0	0	129	0	0
4	250	246	142	0	17	250	0	0	0	0	0	0	0	0	0	0	0	0
5	80	120	250	0	0	185	0	79	0	0	0	0	0	0	0	0	0	0
6	231	157	250	250	250	0	215	245	131	75	204	134	250	0	0	0	21	76
7	0	99	88	2	0	232	0	0	0	0	0	0	0	0	0	0	0	0
8	56	250	62	0	212	236	0	0	0	0	237	0	0	0	0	0	0	0
9	0	0	0	0	0	49	0	0	0	0	9	0	0	0	0	0	0	0
10	0	0	0	0	26	79	0	0	108	0	0	38	48	165	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	218	249	245	122	0	249	0	0	0	0	233	0	250	132	250	235	0	250
13	0	193	1	0	4	27	250	6	250	233	250	138	0	28	27	0	5	0
14	0	9	0	0	0	0	0	0	0	0	3	172	109	0	58	0	0	192
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	12	3	0	0	0	29	0	0	0	0	0	44	0	0	0	0	115	148
17	0	0	0	0	0	173	0	0	0	0	17	0	4	0	0	0	0	0
18	0	0	170	0	0	0	0	0	0	0	0	61	0	0	136	56	0	0
19	0	0	0	0	0	61	0	0	0	0	0	0	30	0	250	0	0	0
20	0	0	0	0	0	238	0	0	0	0	0	95	44	0	0	0	0	0
21	0	0	11	0	0	205	0	0	0	0	25	1	0	0	0	0	0	0
22	107	81	0	0	0	250	0	0	0	0	0	94	110	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	22	0	2	0	0	0
24	3	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
25	0	0	51	0	0	152	0	0	0	0	0	3	20	0	72	0	0	0
26	0	0	0	0	0	2	0	0	10	0	47	0	25	0	0	0	0	0
27	0	107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	26	0	0	0	0	0	0	0	0	101	0	31	0	0	0	0

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Table A.5 – continued from previous page

OD	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
29	0	0	123	0	0	19	0	0	44	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	47	0	0	0	16	1	244	0	250	99	0	0
31	82	35	0	0	0	0	4	0	0	0	0	1	250	0	0	243	0	0
32	0	0	0	54	0	0	60	0	0	72	250	190	250	0	98	4	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	239	0	126	0	0	0
34	0	250	0	0	0	0	0	0	0	0	0	250	0	0	238	75	99	0
35	248	17	0	0	0	250	0	0	133	0	42	250	1	0	171	86	86	2
36	14	0	0	0	0	32	0	0	0	0	159	239	0	0	61	0	0	0

OD	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	213	0	0	0	0	44	0	0	19	86	152	127	0	0	0	0	0	0
2	250	8	14	0	1	105	0	16	26	250	106	0	0	248	110	33	75	250
3	0	0	0	0	0	0	0	0	86	145	0	0	0	250	0	0	0	3
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	14	0	0	0	0	0	250	0	0	0	0
6	63	232	58	0	0	33	36	178	142	250	79	34	35	250	85	112	0	0
7	0	0	0	0	0	0	0	0	0	174	0	0	0	221	0	250	37	84
8	0	0	0	0	0	0	0	0	0	0	39	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	13	0	0	0	0	0	0	21	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	167	0	30	0	0	106	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	84	0	11	15	0	0	212	14	0	205	146	72	0	90	94	238	250	250
13	34	26	1	4	51	0	212	90	0	11	84	250	153	250	131	60	151	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	107	0	42
15	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	193	0	0	206	0	0	39
17	5	4	75	161	2	0	0	108	0	0	0	129	0	0	0	52	0	4
18	0	0	0	0	0	0	0	0	0	0	6	48	0	0	68	88	0	13
19	0	0	0	0	0	0	0	0	57	0	0	0	0	0	0	0	0	0
20	0	0	33	222	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	25	13	0	71	0	0	18	0	0	4	0	13	0	0	0	0	0	79
22	0	0	0	0	0	0	0	3	0	0	0	40	0	0	101	0	0	0
23	0	0	0	0	0	0	0	0	0	36	9	3	0	0	0	0	0	0
24	0	0	0	0	0	0	0	5	0	0	250	53	0	0	0	0	151	0
25	0	0	0	0	0	0	0	0	0	21	56	226	0	0	13	0	0	0
26	0	0	0	0	0	0	0	0	0	0	63	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	83	99	0	0	153	0	0	0
28	0	0	0	0	0	0	0	0	0	0	81	80	0	0	56	0	0	0
29	0	0	0	0	0	6	0	13	66	47	0	0	98	3	0	0	0	0
30	0	0	0	0	0	0	0	0	53	2	0	0	0	137	246	0	0	67
31	0	0	0	0	173	0	95	0	222	95	16	11	0	3	153	0	49	250
32	0	0	0	240	0	144	0	0	0	63	60	250	0	0	235	0	0	242
33	0	0	73	0	0	0	0	0	0	0	0	51	0	32	0	0	0	250
34	0	1	0	0	0	0	0	0	45	0	25	192	0	123	250	0	157	75
35	0	71	0	0	0	0	0	0	129	98	0	3	197	110	177	162	0	174
36	0	0	0	0	0	0	0	0	0	0	0	0	0	88	0	0	0	0

Table A.6: *The resulting OD-matrix for 2040.*

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	313	310	0	218	15	61	54	35	0	0	0	0	0	3	0	0	0
2	313	0	173	311	0	281	309	269	313	0	0	170	239	0	109	151	20	0
3	54	0	0	313	0	133	281	23	0	0	0	254	0	0	0	161	0	0
4	313	308	178	0	21	313	0	0	0	0	0	0	0	0	0	0	0	0
5	100	150	313	0	0	231	0	99	0	0	0	0	0	0	0	0	0	0
6	289	196	313	313	313	0	269	306	164	94	255	168	313	0	0	0	26	95
7	0	124	110	3	0	290	0	0	0	0	0	0	0	0	0	0	0	0
8	124	313	78	0	265	295	0	0	0	0	296	0	0	0	0	0	0	0
9	0	0	0	0	0	61	0	0	0	0	11	0	0	0	0	0	0	0
10	0	0	0	0	33	99	0	0	135	0	0	48	60	206	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	273	311	306	153	0	311	0	0	0	0	291	0	313	165	313	294	0	313
13	0	241	1	0	5	34	313	8	313	291	313	173	0	35	34	0	6	0

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Table A.6 – continued from previous page

OD	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
14	0	11	0	0	0	0	0	0	0	0	4	215	136	0	73	0	0	240
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	15	4	0	0	0	36	0	0	0	0	0	55	0	0	0	0	144	185
17	0	0	0	0	0	216	0	0	0	0	21	0	5	0	0	0	0	0
18	0	0	213	0	0	0	0	0	0	0	0	76	0	0	170	70	0	0
19	0	0	0	0	0	76	0	0	0	0	0	0	38	0	313	0	0	0
20	0	0	0	0	0	298	0	0	0	0	0	119	55	0	0	0	0	0
21	0	0	14	0	0	256	0	0	0	0	31	1	0	0	0	0	0	0
22	134	101	0	0	0	313	0	0	0	0	0	118	138	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	28	0	3	0	0	0
24	4	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
25	0	0	64	0	0	190	0	0	0	0	0	4	25	0	90	0	0	0
26	0	0	0	0	0	3	0	0	13	0	59	0	31	0	0	0	0	0
27	0	134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	33	0	0	0	0	0	0	0	0	126	0	39	0	0	0	0
29	0	0	154	0	0	24	0	0	55	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	59	0	0	0	20	1	305	0	313	124	0	0
31	103	44	0	0	0	0	5	0	0	0	0	1	313	0	0	304	0	0
32	0	0	0	68	0	0	75	0	0	90	313	235	313	0	123	5	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	239	0	126	0	0	0
34	0	313	0	0	0	0	0	0	0	0	0	313	0	0	298	94	124	0
35	310	21	0	0	0	313	0	0	166	0	53	313	1	0	214	108	108	3
36	18	0	0	0	0	40	0	0	0	0	199	299	0	0	76	0	0	0

OD	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	266	0	0	0	0	55	0	0	24	108	190	159	0	0	0	0	0	0
2	313	10	18	0	1	131	0	20	33	313	133	0	0	310	138	41	94	313
3	0	0	0	0	0	0	0	0	108	181	0	0	0	313	0	0	0	4
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	18	0	0	0	0	0	313	0	0	0	0
6	79	290	76	0	0	41	45	223	178	313	99	43	44	313	106	140	0	0
7	0	0	0	0	0	0	0	0	0	218	0	0	0	276	0	313	46	105
8	0	0	0	0	0	0	0	0	0	0	49	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	16	0	0	0	0	0	0	26	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	209	0	38	0	0	133	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	105	0	14	19	0	0	265	18	0	256	183	90	0	113	118	298	313	313
13	43	33	1	5	64	0	265	113	0	14	103	313	191	313	164	75	189	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	134	0	53
15	0	0	76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	241	0	0	258	0	0	49
17	6	5	94	201	3	0	0	135	0	0	0	161	0	0	0	65	0	5
18	0	0	0	0	0	0	0	0	0	0	8	60	0	0	85	110	0	16
19	0	0	0	0	0	0	0	0	71	0	0	0	0	0	0	0	0	0
20	0	0	41	278	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	31	16	0	89	0	0	23	0	0	5	0	16	0	0	0	0	0	99
22	0	0	0	0	0	0	0	4	0	0	0	50	0	0	126	0	0	0
23	0	0	0	0	0	0	0	0	0	45	11	4	0	0	0	0	0	0
24	0	0	0	0	0	0	0	6	0	0	313	66	0	0	0	0	189	0
25	0	0	0	0	0	0	0	0	0	26	70	283	0	0	16	0	0	0
26	0	0	0	0	0	0	0	0	0	0	79	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	104	124	0	0	191	0	0	0
28	0	0	0	0	0	0	0	0	0	0	101	100	0	0	70	0	0	0
29	0	0	0	0	0	8	0	16	83	59	0	0	123	4	0	0	0	0
30	0	0	0	0	0	0	0	0	66	3	0	0	0	171	308	0	0	84
31	0	0	0	0	216	0	119	0	278	119	20	14	0	4	191	0	61	313
32	0	0	0	300	0	180	0	0	0	79	75	313	0	0	294	0	0	303
33	0	0	91	0	0	0	0	0	0	0	0	64	0	40	0	0	0	313
34	0	1	0	0	0	0	0	0	56	0	31	240	0	154	313	0	196	94
35	0	89	0	0	0	0	0	0	161	123	0	4	246	138	221	203	0	218
36	0	0	0	0	0	0	0	0	0	0	0	0	0	110	0	0	0	0

Table A.7: *The traffic volumes and travel times under SO for the initial and second iteration under the 2022 scenario.*

Link	Link OD	x_{a0SO}	x_{a2SO}	t_{a0SO}	t_{a2SO}
. 1	1-4	1624	1624	3.52	3.52
2	2-3	2012	2009	2.75	2.71
3	3-4	1539	1534	1.03	1.03
4	3-8	3751	3731	1.38	1.37
5	3-29	2148	2147	1.55	1.55
6	4-5	1674	1697	0.59	0.59
7	4-8	2238	2253	0.75	0.75
8	5-6	4063	4062	4.47	4.47
9	5-7	2953	2953	1.10	1.10
10	7-8	4691	4629	0.51	0.50
11	7-9	4774	4774	1.05	0.86
12	8-28	1818	1818	1.23	1.23
13	9-10	4435	4427	1.01	1.01
14	9-25	970	972	0.81	0.81
15	10-11	4172	4165	0.64	0.64
16	10-26	670	671	0.61	0.61
17	11-13	2907	2909	4.71	4.71
18	11-14	2941	2932	2.16	2.16
19	12-15	2145	2147	2.07	2.07
20	14-15	3313	3312	1.61	1.61
21	14-17	676	668	6.91	6.80
22	14-26	313	312	4.49	4.49
23	15-16	2600	2605	1.68	1.68
24	16-36	2985	2989	2.71	2.71
25	17-19	782	774	0.95	0.95
26	17-22	464	457	2.71	2.70
27	18-19	1437	1442	2.29	2.29
28	18-36	1658	1614	1.85	1.85
29	19-20	1359	1361	0.82	0.82
30	20-21	490	490	1.43	1.43
31	20-27	721	736	2.24	2.33
32	21-22	663	663	0.58	0.58
33	21-27	353	352	0.82	0.82
34	22-23	786	779	0.45	0.45
35	23-24	991	991	0.81	0.81
36	23-26	172	167	1.32	1.32
37	24-25	717	717	0.50	0.83
38	24-28	1082	1079	1.44	1.44
39	25-26	564	571	1.37	1.37
40	27-28	2434	2467	2.22	2.22
41	27-33	1508	1508	2.97	2.97
42	28-29	1166	1158	1.67	1.67
43	29-30	1031	1026	2.87	2.86
44	29-31	2261	2260	4.43	4.42
45	30-31	1290	1293	2.83	2.83
46	31-32	1654	1653	4.81	4.81
47	31-33	2156	2220	1.95	1.96
48	33-34	2653	2687	2.88	2.90
49	34-36	2457	2494	2.61	2.62
50	35-36	974	974	4.44	4.44
51	4-1	1445	1444	3.51	3.51
52	3-2	3601	3601	2.73	2.82
53	4-3	2302	2382	1.03	1.03
54	8-3	3781	3704	1.36	1.34
55	29-3	2447	2425	1.60	1.59
56	5-4	1905	1965	0.59	0.59
57	8-4	2564	2625	0.75	0.75
58	6-5	3107	3110	4.20	4.20
59	7-5	4441	4476	1.26	1.27
60	8-7	5502	5484	0.68	0.68
61	9-7	5683	5673	0.86	0.95
62	28-8	3307	3342	1.30	1.30

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Table A.7 – continued from previous page

Link	Link OD	x_{a0SO}	x_{a2SO}	t_{a0SO}	t_{a2SO}
63	10-9	4394	4382	1.00	1.00
64	25-9	875	872	0.81	0.81
65	11-10	4347	4335	0.67	0.66
66	26-10	894	896	0.62	0.62
67	13-11	2135	2135	3.60	3.60
68	14-11	2623	2611	2.15	2.15
69	15-12	3992	3996	2.09	2.09
70	15-14	3359	3353	1.62	1.62
71	17-14	511	505	5.75	5.71
72	26-14	469	469	4.66	4.66
73	16-15	2639	2639	1.68	1.68
74	36-16	2752	2753	2.62	2.62
75	19-17	944	931	0.97	0.97
76	22-17	368	368	2.67	2.67
77	19-18	1135	1095	2.28	2.28
78	36-18	1947	1947	1.86	1.86
79	20-19	1039	997	0.60	0.59
80	21-20	272	272	1.38	1.38
81	27-20	787	756	2.73	2.47
82	22-21	712	712	0.58	0.58
83	27-21	365	364	0.82	820
84	23-22	727	727	0.45	0.45
85	24-23	825	826	0.78	0.78
86	26-23	124	124	1.32	1.32
87	25-24	724	724	0.50	0.49
88	28-24	1071	1072	1.44	1.43
89	26-25	562	560	1.37	1.37
90	28-27	2077	2079	2.22	2.21
91	33-27	1561	1579	2.97	2.97
92	29-28	1276	1241	1.67	1.67
93	30-29	959	958	2.79	2.79
94	31-29	1278	1218	4.15	4.15
95	31-30	732	738	2.52	2.52
96	32-31	2082	2080	4.83	4.83
97	33-31	2359	2364	1.96	1.96
98	34-33	1649	1643	2.68	2.68
99	36-34	2221	2222	2.61	2.61
100	36-35	2407	2405	4.47	4.47

Table A.8: *The traffic volumes and travel times under SO for the initial and second iteration under the 2040 scenario.*

Link	Link OD	x_{a0SO}	x_{a2SO}	t_{a0SO}	t_{a2SO}
. 1	1-4	2025	2027	3.55	3.55
2	2-3	2526	2543	2.72	2.72
3	3-4	2212	2494	1.03	1.03
4	3-8	4537	4298	1.76	1.60
5	3-29	2524	2533	1.60	1.60
6	4-5	2442	3118	0.61	0.72
7	4-8	3489	3559	0.77	0.78
8	5-6	4685	4417	4.97	4.71
9	5-7	3309	3309	1.11	1.11
10	7-8	4984	4917	0.55	0.54
11	7-9	5860	5856	0.96	0.96
12	8-28	2188	2035	1.23	1.23
13	9-10	5282	5240	1.37	1.34
14	9-25	1543	1533	0.87	0.82
15	10-11	5284	5256	0.92	0.91
16	10-26	1344	1134	0.87	0.69
17	11-13	3597	3661	8.29	8.87
18	11-14	3698	3814	2.23	2.25
19	12-15	2690	2708	2.07	2.07
20	14-15	4074	4171	1.71	1.73

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Table A.8 – continued from previous page

Link	Link OD	x_{a0SO}	x_{a2SO}	t_{a0SO}	t_{a2SO}
21	14-17	699	704	7.25	7.34
22	14-26	263	241	4.48	4.48
23	15-16	3562	3576	1.73	1.73
24	16-36	4052	4115	4.66	4.90
25	17-19	1066	1063	1.02	1.02
26	17-22	678	613	3.34	3.01
27	18-19	1500	1461	2.29	2.29
28	18-36	1868	1761	1.86	1.85
29	19-20	1611	1532	1.36	1.13
30	20-21	493	449	1.43	1.41
31	20-27	944	928	5.32	4.92
32	21-22	1177	1159	0.59	0.59
33	21-27	417	426	0.82	0.82
34	22-23	1262	1175	0.46	0.46
35	23-24	1311	1199	1.05	0.92
36	23-26	260	254	1.33	1.33
37	24-25	913	840	0.51	0.50
38	24-28	1329	1274	1.84	1.71
39	25-26	1057	1054	1.49	1.49
40	27-28	3028	3245	2.27	2.30
41	27-33	1999	2024	3.00	3.00
42	28-29	1260	1301	1.67	1.68
43	29-30	1226	1122	3.30	3.02
44	29-31	2755	2814	5.19	5.34
45	30-31	1432	1412	3.14	3.08
46	31-32	2268	2305	4.85	4.85
47	31-33	2646	2672	1.98	1.99
48	33-34	3556	3397	4.13	3.75
49	34-36	3028	2836	2.68	2.65
50	35-36	1175	1186	4.44	4.44
51	4-1	1820	1833	3.53	3.53
52	3-2	4453	4530	3.16	3.22
53	4-3	2640	2661	1.03	1.03
54	8-3	4715	4673	1.80	1.77
55	29-3	3244	3362	2.05	2.20
56	5-4	2406	2446	0.61	0.61
57	8-4	3297	3496	0.76	0.77
58	6-5	3832	3855	4.37	4.38
59	7-5	4810	4233	1.39	1.21
60	8-7	6359	5919	1.12	0.85
61	9-7	6291	6098	1.07	1.03
62	28-8	4410	4482	1.70	1.76
63	10-9	5000	5060	1.21	1.24
64	25-9	971	643	0.81	0.81
65	11-10	5163	4955	0.87	0.80
66	26-10	1247	1309	0.77	0.83
67	13-11	2627	2646	3.79	3.80
68	14-11	2924	2772	2.16	2.15
69	15-12	5299	5452	2.23	2.26
70	15-14	3566	3394	1.63	1.62
71	17-14	535	563	5.81	5.93
72	26-14	662	648	6.25	6.02
73	16-15	3152	2972	1.70	1.69
74	36-16	3328	3173	3.13	2.94
75	19-17	1169	1110	1.10	1.05
76	22-17	753	734	4.03	3.82
77	19-18	1402	1303	2.29	2.28
78	36-18	2031	2003	1.87	1.87
79	20-19	1239	1112	0.70	0.63
80	21-20	429	440	1.40	1.40
81	27-20	888	788	4.09	2.74
82	22-21	940	966	0.58	0.59
83	27-21	840	839	0.84	0.84
84	23-22	1229	1238	0.46	0.46

Continued on next page

Table A.8 – continued from previous page

Link	Link OD	x_{a0SO}	x_{a2SO}	t_{a0SO}	t_{a2SO}
85	24-23	893	896	0.79	0.79
86	26-23	470	442	1.36	1.35
87	25-24	820	847	0.50	0.50
88	28-24	1212	1138	1.59	1.50
89	26-25	608	353	1.37	1.37
90	28-27	2483	2433	2.22	2.22
91	33-27	2354	2516	3.07	3.13
92	29-28	1529	1518	1.70	1.70
93	30-29	1206	1185	3.24	3.17
94	31-29	1938	1942	4.24	4.25
95	31-30	1010	1023	2.58	2.58
96	32-31	2598	2630	4.91	4.92
97	33-31	3328	3380	2.12	2.14
98	34-33	3086	3084	3.24	3.24
99	36-34	3397	3368	2.86	2.85
100	36-35	2993	3028	4.57	4.58

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