Demand Responsive Rail Transport

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Applicability of demand responsive rail transport as a substitute for scheduled heavy rail:
a model for relating operational performance of rail DRT to infrastructure capacity.

Master thesis

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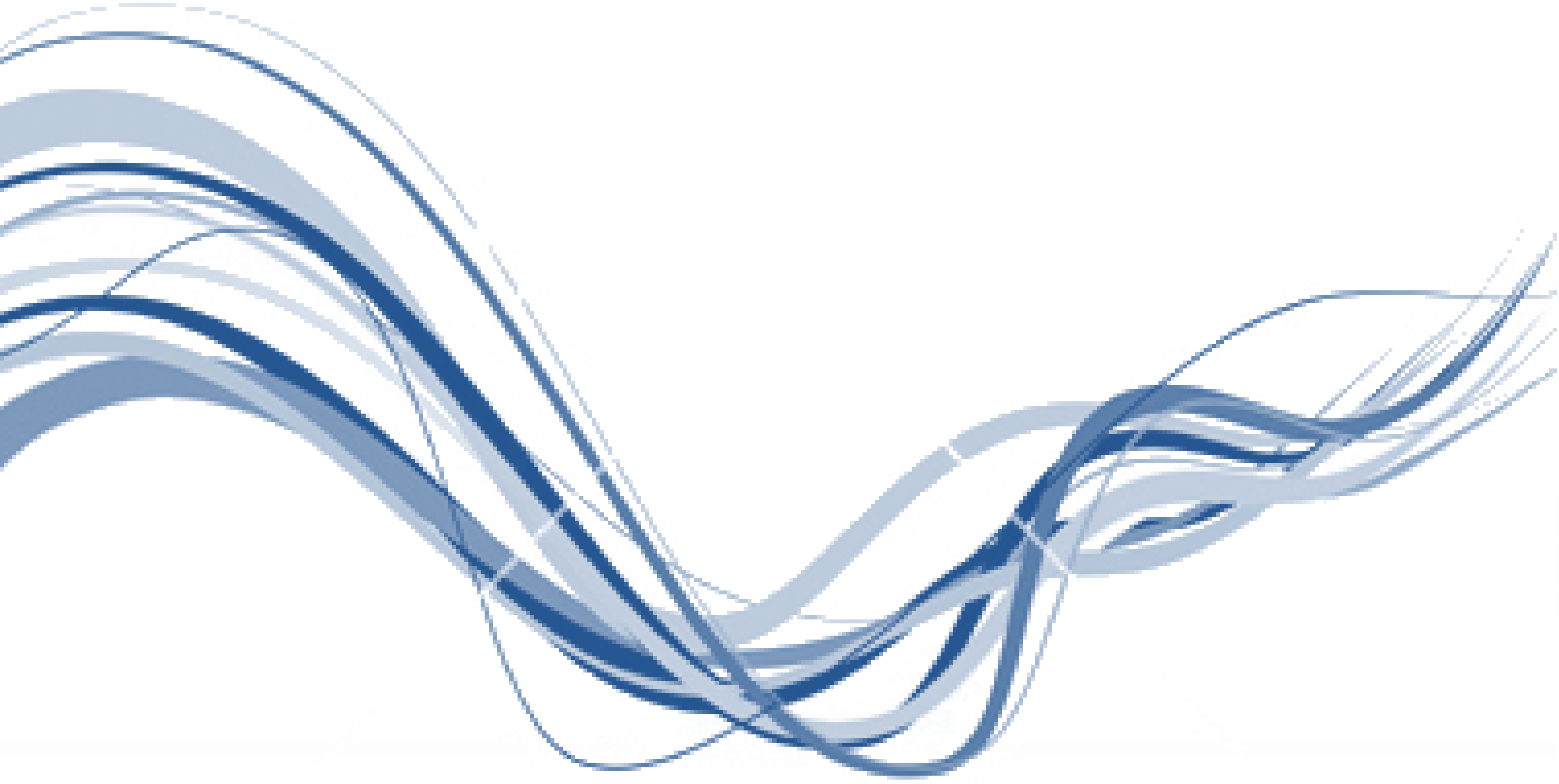
Nederlandse Spoorwegen, 2006

Vision for 2020 ‘Free to move around’.

“Everyone would like to travel without effort. Every time of day. Moment of departure is irrelevant.
NS would like to facilitate services accordingly. Its scope extends beyond a conventional train.”



Preface

Railways have been around in The Netherlands since the first half of the 19th century. Technology has been improving ever since and train travel has become commonplace. What will rail transport look like in future? That is one intriguing question when studying at a University having a slogan ‘challenge the future’. And a challenge it has been indeed, doing research into a future rail concept.

Completing this thesis on demand responsive rail transport would not have been possible without the support of various people. I would like to express my thankfulness to everyone who contributed to my research and who helped me throughout the course of this project. A special gratitude I give to my daily supervisor, Oded Cats, whose innovative suggestions, encouragement, extensive scientific know-how and amazingly quick responses, helped me to accomplish my goals.

I am grateful to Professor Van Arem, who most and for all provided me with the possibility to perform this thesis work. In particular I appreciated his efforts to convince the Faculty’s Board of Examiners that he would guarantee a sound quality of work. To Professor Huisman, I am thankful for his illuminating views on a number of critical issues related to the technical and mathematical details of the project.

A word of thanks is directed to Edwin Boer and Bas Bakker, who were particularly cooperative to get me in touch with the right people for answering my practical questions. Naturally, I shall address special acknowledgements to Wijnand Veeneman, whose flexible and accommodating approach was a prerequisite for finalizing this project.

Ultimately, I would like to thank three people who are most dear to me. First of all, my mother and father, who supported me in any possible way and who have been around to help me whenever I needed them. Secondly, my grandmother, who is no longer with us, but whose unconditional moral support throughout the years was invaluable to completing my curriculum.

I am glad to present my master thesis on demand responsive rail transport. I hope that the reader appreciates its technical focus. May it be an encouragement for further research into innovative technology.

Jesper Haverkamp
Delft, February 16th 2017

Summary

In recent years there has been an increasing interest in the concept of Demand Responsive Transport (DRT). The area of application has almost exclusively been limited to road bound systems. Applying DRT as a substitute for current heavy rail services has not been considered in literature or practice before. This thesis is a first step into the relatively unknown area of rail DRT. It explores the relation between operational performance of rail DRT and network characteristics, in particular infrastructure capacity. The keywords of ‘operational performance’ and ‘network characteristics’ have more formally been defined in the research question as follows:

How do network structure and passenger demand distribution relate to station platform capacity, track capacity, fleet size, level of service and offered seat kilometres in rail DRT systems as a full substitute of scheduled heavy rail?

In this research, rail DRT is considered a full replacement of scheduled heavy rail. Vehicles move around a rail network autonomously, based on passenger requests. Every vehicle may have its own route. Vehicles are sized according to the operator’s preference, but they are considerably smaller than current trains, having 100 seats at most. Passengers are assigned to vehicles such that transfer free travel is offered to as many customers as possible.

S.1 Methodology

A literature study has been conducted into rail DRT. Given the absence of reference material on the topic, the literature study was broadened to include road DRT modelling techniques. Main challenge in any approach is that modelling of DRT requires a dynamic and adaptive system representation, whereas fixed timetables are a comfortable cornerstone in conventional railway models. The synthesis into rail DRT modelling techniques provided three options: rail DRT as a special case of the dial-a-ride-problem, rule based modelling and considering rail DRT as a network flow problem. The latter option has been selected as preferred methodology, whilst the other options were disregarded based on disadvantages such as pseudo-accuracy and incapability of handling large scale networks.

The network flow problem has been redefined to represent a rail DRT system through logical reasoning and by referring to relevant literature, such as the pioneering work in the field of rail DRT by Anderson (1998). The decision variables are arc capacity, node capacity and the share of vehicle flow routed via each available route option between all OD-pairs. The objective is to minimize the cumulative value of infrastructure capacity costs (nodes and arcs), passenger travel time costs and operational costs. These elements are in accordance to common practice in rail cost-benefit analyses. The system is assumed to be run by a single operator, which implies a system optimal case.

The rail DRT model acts at a strategical level and has a deterministic nature. Main input is the network’s passenger demand distribution, which is assumed to be fully known a priori. Demand is uniform over a predefined time period. This is a major difference from earlier models such as by Haverkamp & Maat (2015), which considered an operational model with a stochastic nature of passenger arrivals.

In addition to passenger demand data, input to the model is a network composed of a set of node and arcs, a vehicle size, average load factor, dwell time characteristics, value of time, minimum service frequency threshold, unit infrastructure costs, unit operational costs and unit track capacity. Output is the allocated infrastructure capacity per arc and node, fleet size, the share of vehicle flow per route option per OD-pair and the value of each of the cost components in the objective function.

A logistic function governs the relation between attained speed and density on arcs. Its parameters have been set through comparison to autonomously driving car theories and by considering specific UIC advices. Waiting time at nodes is determined from non-pre-emptive M/M/c queuing theory, where large nodes (more than two platforms) accommodate overtaking of vehicles and hence these nodes have a prioritization system in their corresponding queuing theory equations. This approach was favoured over simpler functions, because queuing theory has the ability to handle the highly heterogeneous service characteristics of rail DRT.

The model has been implemented in Matlab. Main challenge was to find an optimization tool capable of handling a non-linear problem. The model has been verified integrally against fictional networks and in parts using logical checks. Although there is no guarantee of a global optimum solution, the results indicate sufficient model power and reliability. It is capable of solving networks up to at least 30 nodes, 60 arcs and 35,000 passenger requests per hour.

S.2 Results

Both a set of numerical experiments and a case study have been analysed by the rail DRT model. The numerical experiments were performed using a network of 17 nodes, 48 single-direction arcs and 34,000 hourly passenger requests, considering two graph structures: a grid and a ring/radial network, shown in figure s.1. The numerical experiments included a one-variable-at-a-time sensitivity analysis and some combinatorial scenarios. The base case scenario has been developed from comparison of variables to relevant parameters in existing rail networks and by making assumptions with maximum likelihood of justification. A visualization of results in the base case scenario is shown in figure s.2. The input variables of interest in the sensitivity analysis were vehicle capacity, track capacity, arc speed-density relation, operational costs, capacity costs and demand distribution. The combinatorial scenarios were defined based on the results of the one-variable-at-a-time analysis.

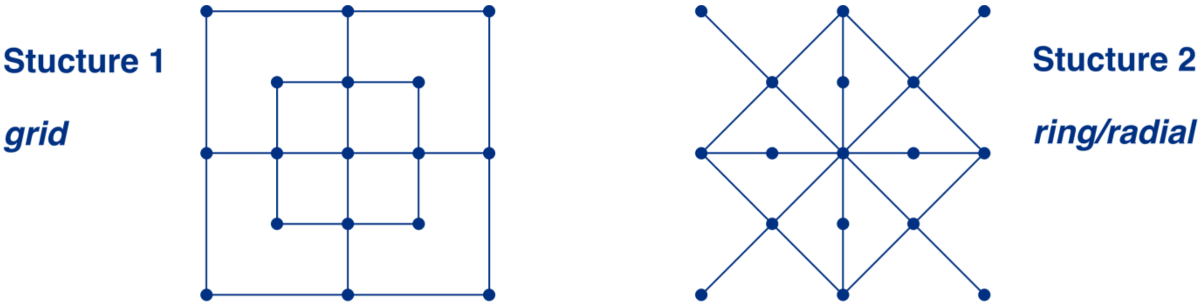
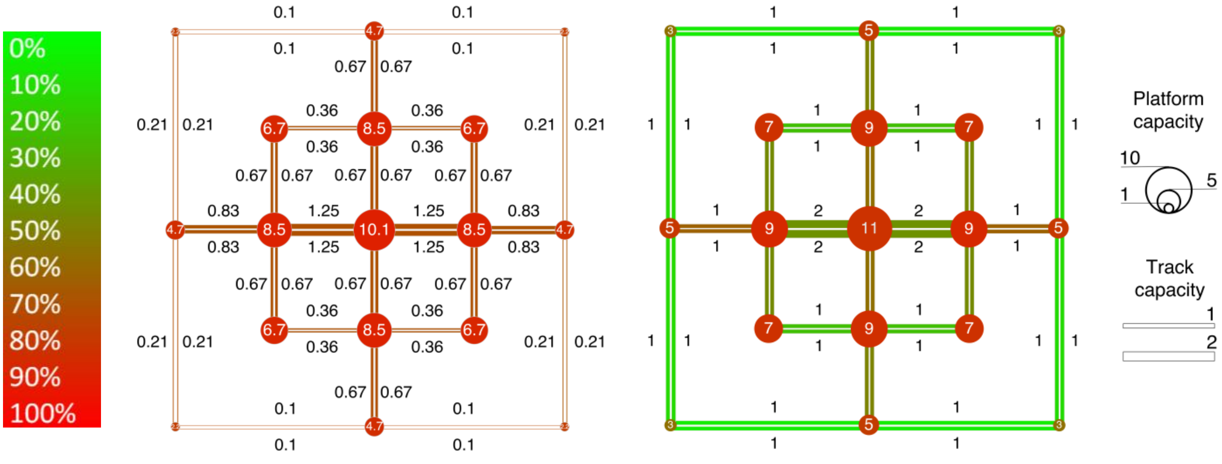


Figure s.1: The two graph structures considered in the numerical experiments. All lines represent bidirectional arcs.



Unrounded infrastructure capacity   *Integer platform and track capacity*

Figure s.2: Allocated capacity (shown by numbers) and corresponding utilization (shown by colours) in the grid network for the base case scenario.

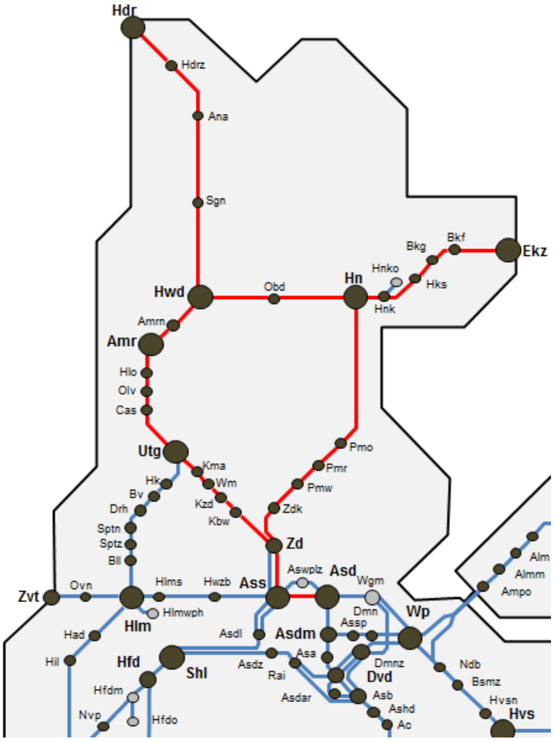


Figure s.3: Case study area (red) in the Dutch railway network.

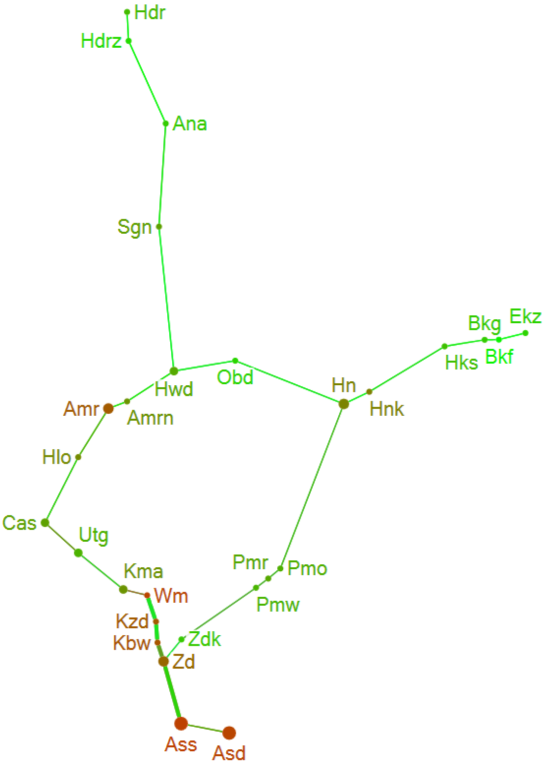
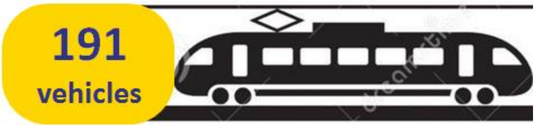
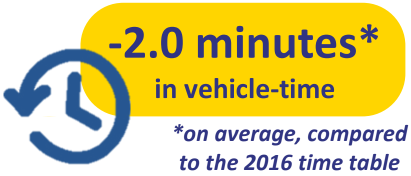


Figure s.4: Visualization of rounded infrastructure capacity (shown by the size of the lines and circles) and corresponding utilization (shown by colours) in the case study for the base case scenario.

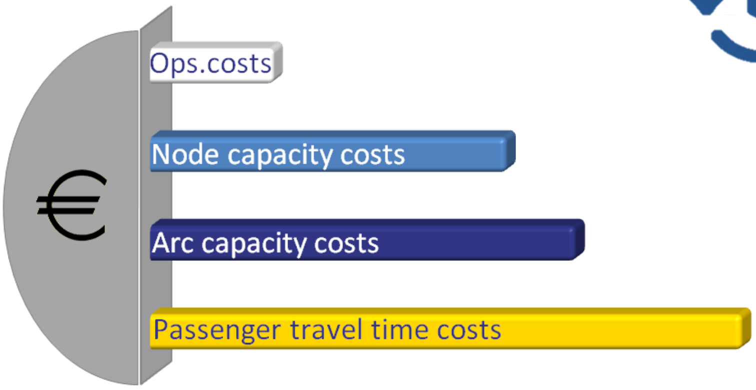
Table s.1 and figure s.5: Case study results in the base case scenario.

Parameter	Units	Value
Arc costs	*[€1000/hr]*	17.94
Node costs	*[€1000/hr]*	14.61
Operational costs	*[€1000/hr]*	5.07
Passenger costs	*[€1000/hr]*	24.32
Fleet size	*[vehicles]*	191
Offered seat kilometres	*[1000 km/hr]*	253.6
Unserved demand	*[-]*	4%
Share of transfers	*[-]*	13%
Service effectiveness	*[Paxkm/paxhrs]*	73
Cost effectiveness	*[€ / paxkm]*	0.35
Average travel time change (in-vehicle time only) compared to the 2016 time table	*[minutes per passenger]*	-2.0





*on average, compared to the 2016 time table



The case-study considered part of the Dutch railway network in the province of Noord-Holland, shown in figure s.3. Current demand distribution and network structure was used as an input. All other input variables were in accordance to the base case scenario used earlier in the numerical experiments. An overview of results is shown in table s.1 and figures s.4 and s.5. One must be aware that in the base case scenario, track capacity is significantly higher than in conventional train systems: 180 vehicles per hour per single direction track. Therefore, this particular input parameter has been studied more closely in the case study. Table s.2 holds the main results.

The average travel time change in comparison to the 2016 time table in the conventional system shows that the rail DRT system offers lower in-vehicle time when single track capacity is higher than 90 vehicles per hour in the case study area. However, this number must not be interpreted as an advised minimum track capacity. Additional data would be required to study this number first. For example, if the development and implementation of a high track capacity is much more expensive than a lower track capacity, the optimal track capacity will be at a different location than in case such a correlation between track capacity and development or implementation costs does not exist.

Table s.2: Case study results of the scenarios with different track capacity.

		Single track capacity in vehicles per hour					
Parameter	**Units**	**30**	**60**	**90**	**120**	**150**	**180**
Fleet size	*[vehicles]*	247	217	206	197	196	191
Service effectiveness	*[Paxkm/paxhrs]*	56	64	68	71	72	73
Cost effectiveness	*[€ / paxkm]*	0.76	0.52	0.43	0.39	0.36	0.35
Average travel time change (in-vehicle time only) compared to the 2016 time table	*[minutes per passenger]*	+4.2	+0.9	-0.4	-1.3	-1.5	-2.0

S.3 Conclusions

The main conclusions are drawn from the combined results of the case study and numerical experiments. They are formulated as follows:

A rail DRT system will offer lowest costs per passenger kilometre when the network is most dense and has best connectivity in the area of highest demand. In practical terms, this implies that stations should be higher in number and closer together in areas of high demand, such as urban regions. In low demand zones, like rural areas, interstation distance should be larger. Else, within the current system definition of rail DRT, there is a risk of a station not being served at all. This actually happened to Zaandam Kogerveld in the case study.

A relatively large fleet is needed to serve only a small part of the customers. The case study indicated up to 50% more vehicles are required just to serve 10% of the customers. Although this 10% of the customers travel longer distances than average, explaining part of the substantial fleet growth, the phenomenon itself raised the (political and social) question whether or not the operator must serve all demand. Naturally, this question is not new in public transport, but one must be aware that the question does not resolve automatically when implementing rail DRT.

Sensitivity of the overall results to changes in unit operational costs are negligible within the range of unit operational cost values suggested by NS. To be more exact, while the value of operational costs rises with increasing seat kilometre price, all decision variables in the model remain untouched. Only once the unit operational costs exceed €0.30 per seat kilometre, will the decision variables be affected. Choices on available infrastructure capacity and vehicle flow routing can therefore be made regardless of unit operational costs.

Allocated node and arc capacity in the case study is comparable to the current system. However, infrastructure utilization is higher, in the order of 70% to 85%, compared to approximately 65% today. It does not always show up clearly in the network visualisation figure, because it uses integer numbers, while the model is based on continuous variables. This difference is illustrated in figure s.2.

Arc capacity is more critical to DRT system performance than node capacity. This is opposite to the current rail network in which stations often are bottlenecks. Moreover, arc costs are very sensitive to the vehicle characteristics of minimum headway and the speed-density relation. Trading-off arc costs against passenger costs (longer travel time) is possible. Another option to limit arc costs is to increase vehicle size. It comes at price of reduced service frequency. One option would be to tailor vehicle size to the demand (introduction of a heterogeneous fleet) to prevent high levels of unsatisfied demand.

Despite being a fundamental element in the model formulation, rerouting of flow via different route options is rare. Only in extreme cases a minor part of the vehicle flow does not take the shortest route. A focus on tailoring of infrastructure capacity to fit with a free flow vehicle distribution, is considered more beneficial for the objective function than to include the complex rerouting option.

S.4 Discussion and points of attention

The key findings identified a strong interaction between the system definition, model formulation and final results. Therefore, for the rail DRT operator it is important to state clearly what the exact DRT system definition will be, including choices on service type. This also relates to load factor. An average load factor of 70% was used throughout this thesis. The operator may require to have a seat for everyone or accept that people stand upright during some periods of day. Therefore, it is suggested for future research to run the rail DRT model with load factors exceeding unity. This is expected to have consequences for the required infrastructure capacity, because a change in load factor is equivalent to a change in vehicle size, since it affects the service frequency per OD-pair.

The applied method to transform the passenger OD-matrix into a service frequency table under the limitation of a frequency threshold has implications for low-demand OD-pairs. This is particularly relevant when benchmarking rail DRT to the conventional system. Also, there is a risk of not serving long-distance passengers, because their numbers are often small, while they generate a substantial share of revenue.

Queuing theory is a fundamental element in the rail DRT model. It is based on the assumption of Poisson distributed vehicle arrivals at nodes. It was identified that this assumption may not be valid in case of multiple sequential low capacity stations. Therefore, it is suggested to explore if another distribution would be more accurate a representation of vehicle arrivals at these stations. The corresponding implications on the queuing theory equations should naturally be considered as well.

In the case study, this thesis applied current passenger data straight to the rail DRT model, while the introduction of rail DRT could influence demand patterns and passenger flows. Studying the effects of rail DRT on passenger demand distribution, station attractiveness and travel behaviour is a suggestion for an entire study on its own. In addition, DRT offers new possibilities for concessions and tendering. Having smaller vehicles, shorter headways, higher frequency and less network coherence (more point-to-point transport), there are little objections against multiple DRT operators running their vehicles simultaneously like a taxi service. From the perspective of the rail DRT model, such a system would require a redefinition of the objective function, because multiple operators are more likely to behave in a user equilibrium state.

Ultimately, the thesis results are interesting and enlightening. They offer sufficient thoughts and suggestions for further research into rail DRT. May the results inspire further development of rail DRT, possibly even a real-life system for testing purposes.

List of abbreviations

AGT	Automated Guideway Transit
CVV	Collectief Vraagafhankelijk Vervoer
DARP	dial-a-ride problem
DB	Deutsche Bahn
DRT	Demand Responsive Transport
ERTMS	European Rail Traffic Management System
hr	hour(s)
km	kilometre(s)
min	minimize
n.a.	not available
nr.	number
NS	Nederlandse Spoorwegen
OD	Origin – Destination
ops.	operational
pax	passengers
PRT	Personal Rapid Transit
ring/rad	ring/radial network
SNCF	Société Nationale des Chemins de fer Français
SRQ	sub research question
UIC	Union Internationale des Chemins de fer
veh	vehicles
VOT	value of time

It is assumed that the reader is familiar with the abbreviations and nomenclature of Dutch railway stations.

List of symbols

A	Set of arcs
A_L	Set of arc lengths
A_v	Set of arc free speeds
a	Arc index
b	Number of OD-pairs in the network
C	Maximum continuous capacity utilization according to UIC advice
c_a	Capacity of arc a
D	Set of nodes which are a demand point
d	Destination node index
$d^2_{(o,d)}$	Squared Euclidian distance between origin o and destination d
E_1	Hourly costs of track infrastructure capacity
E_2	Hourly costs of station platform capacity
E_3	Operational costs per seat kilometre
E_4	Passenger value of time
F	Fleet size
$f_{r_{max}}$	Maximum allowed detour factor for selecting route options
f_{v_a}	Speed reduction factor on arc a
g	Dummy variable of hourly service requests at a node
h	Priority class index
i	Node index for any node from which the node with index j can be reached directly
j	Node index
k	Node index for any node which can be reached directly from the node with index j
L_a	Length of arc a
$L_{p_{fix}}$	Platform length, fixed component
$L_{p_{var}}$	Platform length, vehicle dependent component
l	Number of arcs in the network
m	Summation index
N	Set of nodes
n	Number of nodes in the network
n	Number of requests in a dial-a-ride-problem
o	Origin node index
OD	Set of OD-pairs
P	Hourly OD-matrix
P_{total}	Total hourly passenger demand in the network
p	Number of demand nodes in the network
q	Demand node index
r_{od}	Number of route options for OD-pair (o,d)
r_a	Cost (in time or money) of unit transhipment along arc a
s_j	Capacity of node j
s_{prio}	Number of platforms required to have a priority system in queuing theory
T	Total number of time steps considered during modelling
$T^{(o,d)}_{veh}$	Total travel time (in-vehicle) of all passengers from origin o to destination d
$T^{(o,d)}_{w}$	Total travel time (waiting) of all passengers from origin o to destination d
t	Time step index
t_d	Dwell time
u_j	Binary dummy variable which states if node j has a prioritized queuing system (1) or not (0)

V_a	Speed of vehicles running on arc a
$V_{a_{free}}$	Free speed of arc a
v_{min}	Minimum hourly service frequency in order to have a service
$v_{(o,d)}$	Hourly frequency of service on OD-pair (o,d)
W_j	Waiting time at node j
W_{j_h}	Waiting time at node j in priority class h
w_1	Link capacity weight factor
w_2	Node capacity weight factor
w_3	Operational costs weight factor
w_4	Travel time costs weight factor
$w_{(o,d)}$	Gravity factor between origin o and destination d
w_{total}	Cumulative gravity factor over all OD-pairs
x_a	Flow on arc a
x_d	Horizontal position of destination node d
$x_{(i,j)}$	Flow on the arc from node i to node j
x_d	Horizontal position of destination node d
x_o	Horizontal position of origin node o
x^d	Flow having destination d
$x^{(o,d)}$	Flow originating at o having destination d
$x_j^{(o,d)}$	Flow into node j if $(o \neq j)$ or out of node j if $(o = j)$
$Y_j^{(o,d)}$	Stochastic variable indicating the number of hourly service requests at node j made by vehicles originating at o having destination d
y	Maximum number of vehicles per hour per unit of arc capacity
y_d	Vertical position of destination node d
y_o	Vertical position of origin node o
z	Vehicle seating capacity

α	Scaling parameter of the logistic speed-density function
β	Shifting parameter of the logistic speed-density function
λ	Event rate parameter of a Poisson distribution in general
λ_j	Event rate parameter of the Poisson distribution describing hourly service requests at j
λ_{j_h}	Event rate parameter of the Poisson distribution describing hourly service requests at j in priority class h
μ_h	Inverse of the mean service time for a vehicle in priority class h
μ_j	Inverse of the mean service time for all vehicles being serviced at node j
ξ	Average vehicle load factor (occupied seats to available seats)
Π_j	Delay probability at node j
ρ_j	Density (intensity to capacity ratio) at node j
ρ_{j_h}	Density (intensity to capacity ratio) at node j in priority class h
φ_a	Intensity to capacity ratio on arc a

List of figures

List of tables

Table of contents

1. Introduction

In recent years, the concept of Demand Responsive Transport (DRT) has been broadened from a niche market to a more commonly applied system of transportation (Mulley & Nelson, 2009). Nevertheless, the area of application has almost exclusively been limited to road bound systems. Studies into viability of rail bound DRT concern small scale applications only, such as people movers, systems for feedering main line networks (Juster & Schonfeld, 2013) and systems for increasing catchment area of large multimodal transfer nodes (Andréasson, 2012).

Applying DRT as a substitute for current heavy rail services has not been considered in literature or practice before. An exploratory research has been conducted into performance of rail bound DRT by Haverkamp & Maat (2015). The study focused on the interaction between passenger requests and vehicle circulation in the network. Considerable reduction in travel time and an increase in load factor were predicted compared to traditional supply driven systems. The nature of the research and its available resources imposed some restrictions. In first place, the applied model did not consider any optimization or objective function. Secondly, line and station capacity and other related infrastructure parameters were excluded.

Resolving the aforementioned deficiencies and expanding the scientific knowledge on the relatively unknown field of rail DRT was suggested for further research. In accordance to the suggestion, this thesis explores the relation between operational performance of rail DRT and network characteristics, in particular infrastructure capacity. Thesis results are not just of scientific relevance. Dutch railway operator NS expressed their interest in a follow-up study for the 2015 exploratory research. This dual interest and corresponding objectives are discussed in section 1.1. A more formal definition of ´operational performance´ and ´network characteristics´ is provided in section 1.2. Also, the research questions are presented in section 1.2. Section 1.3 describes the thesis scope and lists assumptions and definitions. Finally, section 1.4 addresses the project´s approach and expectations.

1.1. Objectives and interests

In 2015, Dutch railway operator NS expressed their interest in demand responsive rail transport: "*From the perspective of product innovation, NS is considering options for future transport concepts. Currently, the railway system operates in a supply driven manner with trains running in accordance to a fixed, predefined schedule. Being inspired by recent developments on automated driving in the car industry, NS would like to explore the possibilities of demand responsive transport by rail.*"

Following the request from NS, an exploratory research has been conducted in 2015. Motivated by the results of that research, NS would like to explore rail DRT in more detail. In particular, NS is interested in judging the concept of rail DRT as a future substitute for scheduled heavy rail. Ultimately, NS wants to know if, and if so in which parts of their network, DRT offers better service to customers or lower operational costs compared to conventional supply driven systems; and what investments are needed to be able to operate DRT. NS emphasizes that the latter specifically refers to infrastructure and fleet investments.

The scientific interest on this topic is closer related to exploring the relatively unknown field of rail DRT and study methods to model it. More explicitly for this thesis, the scientific interest is to gain insight into the relation between operational performance and network characteristics. The thesis project shall reflect this scientific interest, whilst keeping the boundaries of the project such that NS' interests are still sufficiently involved. A comparison between both interests is provided in figure 1.1.

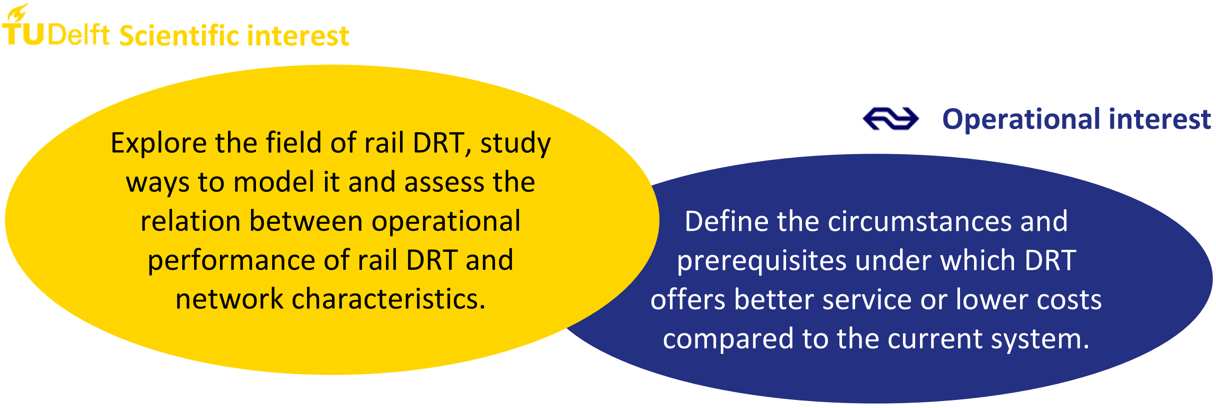


Figure 1.1: Comparison between the scientific interest and operational interest in this thesis.

1.2 Research questions

Keywords in the project´s scientific interest are ‘network characteristics’ and ´operational performance’. Setting up the research questions first requires a more formal definition of those two terms. There is no official international standard for classifying railway networks or railway performance. In the United States a classification system exists which is revenue based rather than based upon network characteristics. Hence, it is not applicable to this study. The suggestion of railway performance indicators by Yu (2008) is considered more comprehensive: network size (rail length), fleet size (number of cars), workforce (number of employees), train kilometres and passenger kilometres.

Note that some of Yu’s indicators are not applicable to rail DRT, because of the very nature of the system. These include workforce size (due to automated vehicles) and train kilometres (due to the vast difference between current train size and vehicle size in DRT resulting in incomparable train kilometre figures). Train kilometres are replaced by offered seat kilometres as a more representative indicator. Furthermore, rail length does not capture the network characteristics of station quantity, inter-station distance and network connectivity. Therefore, rail length is exchanged for network structure. Finally, station platform capacity and track capacity are added to capture the research’s infrastructure component. Level of service is taken into account as well because it is a key element for assessing DRT service effectiveness. Passenger kilometres is replaced by a more comprehensive alternative: passenger demand distribution.

The main research question is defined as follows:

? ***How do network structure and passenger demand distribution relate to station platform capacity, track capacity, fleet size, level of service and offered seat kilometres in rail DRT systems as a full substitute of scheduled heavy rail?***

Answering this main research question will satisfy both the scientific and operational interest. The research question is adequately broad to allow for exploring the field of rail DRT, while it is sufficiently specific to be able to assess the relation between operational performance and network characteristics. Simultaneously, the comprehensive set of performance indicators encompassed in the research question offers ample possibility to evaluate the rail DRT system from the operator’s perspective.

To allow for answering the main research question properly and structured, a set of sub questions is defined. The method of untying core concepts has been used to set up the first two sub questions.

A key aspect to answering the main research question is a proper definition of parameters and units. Also, it must be clear what rail bound DRT actually is. Hence, the first two sub questions pose:

SRQ1 What are the (technical) system characteristics of rail bound DRT considered in this research?

SRQ2 How, in terms of units and level of detail, can the performance indicators best be expressed?

Recall that one of the scientific interests in this research is to study models for rail DRT systems. The method of supportive types of knowledge defines the third, fourth and fifth sub research questions. They focus on the modelling aspect. An essential element in modelling is to have an aim or objective. This is addressed in the fourth research question. Factors of influence are studied in the third research question. Finally, the fifth research question concerns the actual model development itself. It ensures that the most appropriate model is used.

SRQ3 Which system characteristics are factors of influence affecting the relations mentioned in the main research question?

SRQ4 Which input, output, decision variables, objective and constraints govern the rail DRT model?

SRQ5 Which model is preferred such as to attain sufficient accuracy and limited complexity in solving the optimization problem?

1.3 Scope boundaries, definitions and assumptions

In contrary to the major part of earlier research on DRT systems, which mainly concerned road bound transport, this study focusses solemnly on rail bound DRT. Hybrid solutions of road and rail combinations are not considered. Moreover, the research is limited to DRT as a substitute for current scheduled heavy rail. This means that the system offers station-to-station transport rather than door-to-door service like taxi systems. Furthermore, there is no mixed traffic in the sense of rail bound DRT operating as a complementary service to regular trains.

The DRT system in this research is a full replacement of scheduled train services. Nevertheless, the application in practice could be that DRT is introduced on part of a network, with transfers to the supply driven segment of the network being offered at interchange stations.

1.3.1 Defining rail DRT

In this thesis, rail DRT is considered a system of autonomous vehicles moving around a network without a-priori timetabling involved. Routing and scheduling is based on real-time passenger requests (although for modelling purposes the demand is assumed to be known on forehand). Every vehicle may have its own route. Vehicles are sized considerably smaller than current trains (this will be addressed in more detail in chapter 5 on scenario development). Passengers are assigned to vehicles such that transfer free travel is offered to as many passengers as possible. Deadheading of vehicles is allowed to offer better level of service or attain higher system efficiency. The system is run by a single operator. Implications of a DRT system on travel behaviour are not considered. Chapter 3 elaborates on these definitions and their consequences.

An ideal scenario is assumed to apply, without any service disruptions. There are no knock-on effects from connecting networks at interchange stations. Consequently, network robustness, stability and resilience cannot be studied. Freight transportation is omitted in the DRT system. While this assumption cannot hold for practical applications, it is introduced to limit the scope of the research within reasonable bounds. Mixed traffic of similarly sized freight and passenger vehicles is an option for future research.

1.3.2 Input and output

Note that the main question calls for studying the relation between a number of performance indicators and network characteristics of rail DRT. The question does not define which of those are input and which are output. Such definition is provided next.

Starting point is a railway network with a given travel demand. More specifically, a set of nodes and arcs is available, as well as an OD-matrix (for various times of day if necessary). The aspect of demand distribution is captured by the OD-matrix. Level of service could be either input or output. When level of service is an input, it acts as a constraint. The rail DRT model will show if the defined level of service can be attained (feasible solution) or not (infeasible solution). When level of service is an output, there will always be a feasible solution. One has to assess if the attained level of service is acceptable or not. An exact definition of 'level of service' and its implementation is part of the research and hence this aspect has been included in the third research question.

Certain operational constraints are in place. These include a starting scenario for the available infrastructure, vehicle capacity and operational speeds. Formulation of those constraints is part of the research. An objective function must be defined to optimize the rail DRT system for (total) costs or some other aim, while meeting all of the aforementioned input constraints. Infrastructure capacity is one of the core decision variables. Fleet size and offered seat kilometres will be output. The exact formulation depends on the choice of the modelling approach. This is addressed extensively in chapter 3, including a schematic overview in figure 3.1.

1.4 Approach and expectations

This master thesis involves theoretical research rather than empirical. Experiments and observations in practice are impossible, because no rail bound DRT system is in operation yet. Consequently, model development can be considered the core element in the master thesis project.

Developing a proper model starts with conducting a thorough literature study. Although it has already been identified that studies into rail bound DRT are rare, it is worthwhile to explore the details of such studies. Moreover, examining best practices from modelling DRT systems in other areas of application is useful too. The literature study is supportive to the model development. Chapter 2 discusses the results of the literature study. It concludes with a synthesis into modelling options for rail DRT.

Model development concerns setting up an objective function, set of constraints and decision variables. Also, a choice of modelling technique must be made. This includes critically reviewing the 2015 exploratory research model. It is valuable because it prevents unnecessary mistakes and avoids additional work. One aspect which lacked in the 2015 model development process was verification and validation. It is assured that this is included for the new model. Chapter 3 presents the rail DRT model and describes the development process. Model implementation is discussed in chapter 4.

Once the model is completed, a variety of input scenarios are run. The scenarios are defined such that the relations mentioned in the main research question can be studied. A set of numerical experiments is performed for this purpose. Chapter 5 concerns these numerical experiments. The chapter elaborates on scenario development and presents the corresponding modelling results. A case study is performed in chapter 6.

Conclusions of this thesis are valuable for both NS and the scientific interest. Results could be used as a basis for more in depth analysis of specific aspects of rail DRT, such as vehicle interaction or vehicle dispatching. Moreover, the results could inspire further development of rail DRT, possibly even a real-life system for testing purposes. Chapter 7 holds the conclusions and recommendations.

2. Literature study

'Timetable-free travel' is the popular name given to the intended high frequency services on trunk routes in the Dutch rail network by 2018. Although the nomenclature suggests a demand responsive system, train services will still be supply driven with a fixed, pre-defined schedule. 'Timetable-free' simply refers to the reduced need to plan a journey in advance. French railway company SNCF did introduce a quasi-demand-responsive service in 2015. Named *#tgvpop*, SNCF offers optional trains as a complement to the regular time table, with those trains running only when sufficient votes have been collected via social media. Although *#tgvpop* is not strictly rail DRT according to the definition in this thesis, the service is the only existing example to date which is some form of demand responsive heavy rail. The following literature study addresses this absence of existing rail DRT systems. The chapter also covers related other mode DRT and presents a critical review of existing literature.

Four topics are discussed in the literature study as a basis for the model development phase. First, the self-defined phenomenon of the 'rail DRT paradox' is introduced in section 2.1. DRT systems are briefly presented in 2.2. Relevant work on rail DRT and related topics is critically reviewed in section 2.3. The chapter concludes with an overview of approaches for modelling rail DRT in section 2.4.

2.1 The rail DRT paradox

Numerous modes of public transport exist, ranging from frequent metro systems to occasional bus services. All modes have certain characteristics such as typical capacity, operational speed, density and coverage, accessibility, operational costs and various other parameters. To each mode, one could assign an 'area of application' in terms of the aforementioned indicators. This area of application provides an indication to planners and operators which mode of public transport is most suited under which circumstances. Figure 2.1 shows the relation between typical ridership and travel distances of various public transport modes in The Netherlands and (foreign) DRT (there are hardly any DRT systems in The Netherlands). Please refer to appendix A for the underlying data. It appears that conventional DRT systems and heavy rail services are at opposite sides of the spectrum. Combining heavy rail and DRT seems contradictive. This will be referred to as the rail DRT paradox.

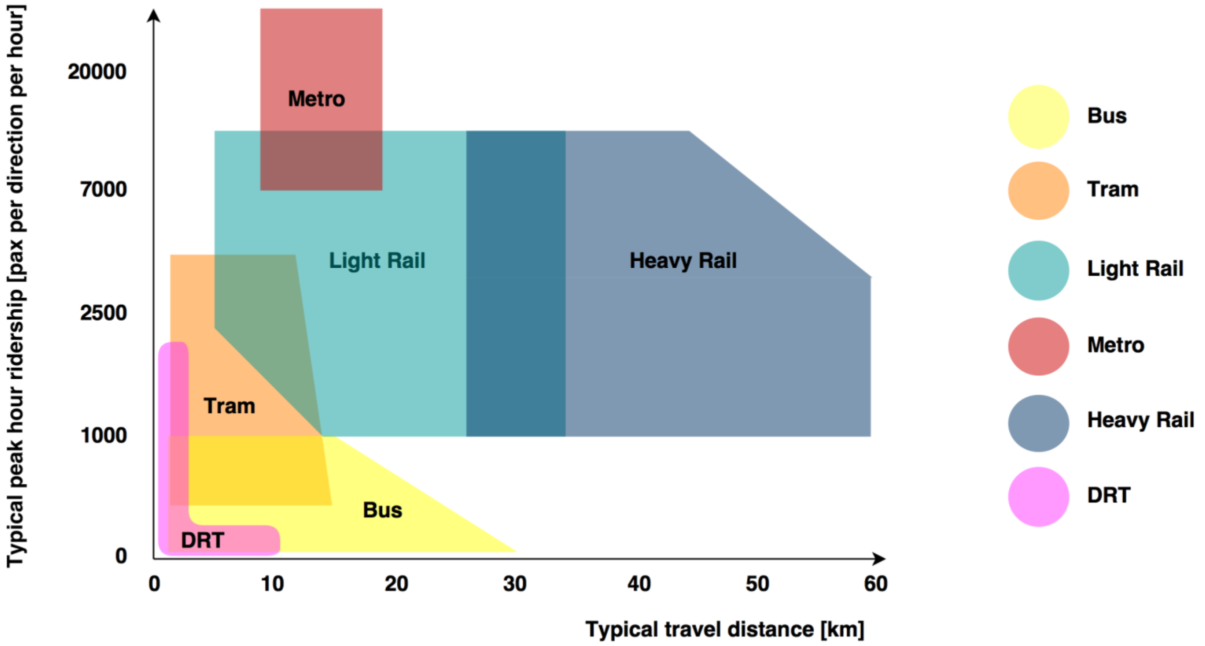


Figure 2.1: Typical ridership and travel distances of various public transport modes in The Netherlands and (foreign) DRT.

The rail DRT paradox is endorsed by the research of Mageean & Nelson (2003). They conducted an evaluative study into existing DRT systems in Europe based on three indicators: economic viability, service provision and technical performance. A total of 15 DRT systems across Europe were assessed. Mageaan & Nelson concluded that “The original objectives of DRT were to cater for widely dispersed trip-patterns and to provide a service in low-density suburban areas for mainly non-work journeys”, which is vastly different than heavy rail serving high density (commuter) routes. Mageaan & Nelson even emphasize the apparent impossibility of combining DRT and high ridership numbers: “Services have often been criticised because of [..] their inability to manage high demand.”

Given the rail DRT paradox, the question arises if it is wise to pursue rail DRT after all. Nevertheless, one must realize that the rail DRT paradox is based on historical data. Innovations in (rail vehicle) technology, such as the ongoing RailCab project at the University of Paderborn (Dangelmaier et. al., 2001), could change the traditional landscape of transport modes. An increasing interest in demand responsive services may accelerate such developments. Brake, Nelson and Wright (2004) endorse this philosophy: “Ideally, public transport would be as convenient as private transport, suggesting that all public transport should be demand responsive.”

The fact that rail DRT has never been implemented before could also be considered a stimulus to study and explore this field rather than an inhibitory factor. Perhaps this thesis could be a first step to change the perception described by Bakker (1999): “DRT is considered only to be an option for far away countries and for market-niches like elderly and disabled people in the Western world. This perception is based on experience with various small scale experiments with new forms of public transport that were undertaken in the past and which more often than not showed poor results in terms of user numbers and cost coverage.”

Still, the rail DRT paradox calls for caution and reminds us to keep a critical attitude toward feasibility of rail DRT throughout the thesis work. It is important to learn from past experiences. Enoch et. al. (2006) identified 72 failed DRT projects (not necessarily rail related). They analysed the underlying causes of each failed project by interviewing users, operators, governmental bodies and other stakeholders. The conclusion states: “There is a very dangerous temptation to offer too flexible a service and to include costly technological systems, when they may not be needed.” Anderson (2000) elaborates in his review on the technology’s state of the art: “It is a complex technology, although not as complex as many systems now in daily operation; there are many ways to do it wrong and only a few ways to do it right.”

In addition to the rail DRT paradox, four barriers have been identified which add uncertainty to a successful development and implementation of rail DRT. These four barriers and the most important stakeholders associated with them are discussed next. The discussion serves to enlighten the reader about these barriers, rather than as an argument why rail DRT could possibly fail.

1) Innovation is required to develop the existing rail technology into a properly functioning DRT system. Currently, all actors involved show little interest in moving forward in this area. Operators are mainly satisfied with their current abilities to serve the transportation market. This effect is enhanced by the heavily protected railway market itself which has little internal competition. Product manufacturers are comfortable with this phenomenon. It provides them with a predictable and stable market. Therefore, they do not feel an urge to change their strategy. Recent developments in the car industry on automated driving, could change this attitude. However, the rail industry unfortunately is known to be slow in changing, an effect which is even more prominent when legislation needs adaptions as well.

2) Implementing rail DRT requires a full system change. Hybrid solutions of traditional heavy rail and novel DRT are very complex. Various experts in the field consider a gradual transition to be impossible or at least highly unlikely due to the complexity. A full system change on a national scale has not been done before. Some regional railway lines have been transformed into light rail in recent years. However, the area affected during reconstruction was relatively small and the effects could be mitigated. Proper coordination between governmental bodies, infrastructure managers and operators is vital to ensure a proper system implementation.

3) Rail DRT is associated with high investment costs. This is related to the previous issue of a full system change. The rail DRT system has to be created from scratch, while the current system is fully operational and only requires maintenance and updates.

4) Current developments and visions about the future of rail transport counteract some of the rail DRT system requirements. This includes for example the current focus on reconstructing and expanding the major railway stations in the network, while in rail DRT the increased attractiveness of local stations may call for a focus on those station instead. To prevent unnecessary investments and to ensure that rail DRT can still be implemented successfully in future, the concept of rail DRT should be considered and included in visions and reports today. However, the rail industry has a relatively long term scope with little room for innovations on a scale like DRT. Also, a change is in attitude may be required at policy makers.

2.2 A brief introduction into (rail) DRT

Currently, demand responsive transport has a limited share in passenger volumes and passenger kilometres amongst all modes of public transport (Ryley, et.al, 2014). This phenomenon does not come as a surprise. Public transport is based on aggregating people in time and space. In other words, multiple passengers are carried in one vehicle via a common route. A predefined schedule appears a prerequisite to enable successful aggregation of customers. Yet, there are options for public transport without timetable, as proven by existing DRT systems, which are discussed next.

Operating conventional public transport services is a challenge in areas with low travel demand or low population density. In rural areas or places with extensive urban sprawl, the number of passengers is too small and their origins and destinations are too segregated to operate conventional public transport services at acceptable costs. Combining transport services for elderly and disabled with public dial-a-ride services is a common solution to this problem in the Netherlands, known as ‘Collectief Vraagafhankelijk Vervoer’ (CVV). Globally, likewise to the Dutch example, DRT is often applied in low yield areas as a substitute for conventional public transport.

In the 1960s and 1970s there was a particular scientific interest in DRT, or more generally in dial-a-ride problems (DARP). The interest was triggered by positive comments in the influential reports by the United States Department of Housing and Urban Development. Extensive pioneering work has been done by Wilson (1971). In a series of MIT Reports on DARP. Wilson created a solid basis for later research. Many DRT and DARP studies still refer to his work. The simple, yet effective definitions Wilson created offer possibilities to be extended and tailored for more complex research purposes.

A larger scale application of DRT is rare. Helsinki’s Kutsuplus and Boston’s Bridj are the most extensive DRT systems in operation to date. Both are city-wide networks offering urban service with mini-vans which adapt and optimize their routing according to real-time passenger requests. The networks could be considered larger scale dial-a-ride systems. Nevertheless, neither one of those bus systems is rail DRT.

2.3 Relevant work on rail DRT and related systems

To this date, only one system fits the definition of rail DRT in this thesis. It is the earlier mentioned RailCab project at the University of Paderborn. Started in 1997, the project studies technical feasibility of operating small rail vehicles at short headways (in the order of seconds). Its main focus is on vehicle dynamics and guidance. Although a test segment is in operation at the University, no reports with (intermediate) results or even a methodology are available. Publications are limited to presentations about the concept during conferences (Dangelmaier et. al., 2001). Figure 2.2 shows the RailCab test segment in Paderborn.

Figure 2.2a & 2.2b: The RailCab project test segment in Paderborn, focussing on rail DRT vehicle technology.

When widening the scope from strictly rail bound to Automated Guideway Transit (AGT) in general, there are more systems of interest. The state of the art overview by Ellis et. al. (2014) provides a comprehensive insight. Unlike traditional road DRT systems such as the earlier discussed CVV, the work by Ellis et. al. shows that AGT is often applied in high demand situations. In contrary to CVV, the number of destinations in AGT is small and network structure is simple. Most AGT systems are line networks in which the only demand responsive aspect is the number of intermediate stops. Systems operate like a horizontal elevator. The example of AGT which, in terms of network complexity, comes closest to the definition of rail DRT in this thesis is the Cabinentaxi system, an urban DRT monorail intended to cover the entire city of Hamburg. Although a test segment was in operation by 1974, the system was never implemented due to adverse car lobby (Bendix & Hesse, 1972).

In the Cabinentaxi study, Bendix & Hesse identified the challenges of short vehicle headways and limited station capacity. Vehicle design solutions for operating at such short headways in an AGT system have only been studied many years later by Choromanski & Kowara (2011), while capacity in relation to station layout has been analysed in more detail by Greenwood, Mantecchini & Schweizer (2011). The shortest known headway in operation to date is 20 seconds at Paris' SK system.

Like the Cabinentaxi study, both of the aforementioned researches focused on simulation of advanced vehicle technology rather than looking at operational performance of the system. Hence, albeit enriching background knowledge, these past researches do not provide a starting point for the model to be developed in this thesis. To the best of my understanding, there is only one author who conducted research which is related to this topic: Anderson.

Major pioneering work on DRT and AGT systems, with a focus on Personal Rapid Transit (PRT) in particular, was done by Anderson. He contributed to over a dozen journal articles on the topic, studying a variety of aspects of AGT such as operational costs, service robustness, capacity, energy consumption and reliability (Anderson, 2000). This made his work vastly different than most other research in the field, which focused on the technical feasibility aspect only.

Anderson (1998) developed a model for simulating AGT systems. The model was command driven and had a microscopic nature. It considered all vehicles in the system separately. Every time step, the status of a vehicle was updated based upon its previous status and any commands given to the vehicle. Anderson defined a vehicle-location-dependent set of commands. Based on travel demand, the commands were given according to pre-defined rules. Objective of the model was to generate highest throughput in the system, although Anderson did not specify explicitly why the approach should result in highest throughput. Output parameters included average and maximum passenger waiting time and variation thereof. Results were generated for a virtual network of 15 stations and 343 vehicles. The model was limited by computation capacity of the available computers.

Considering the advances in computer technology over the years, Anderson's AGT model may be applied to larger networks today. However, a major drawback is the lack of an objective function or optimization. The model does not contain decision variables. The solution it will provide is 'a' solution, not necessarily the best solution.

The approach by Anderson shows similarities with the exploratory research into rail DRT conducted by Haverkamp & Maat in 2015 (although the authors were not aware of the work by Anderson at the time of their model development). The study assumed a hypothetical system of autonomous rail vehicles moving across a network unrestrictedly, with routing and scheduling based on real-time passenger requests. A rule-based vehicle assignment model was deployed to analyse performance in terms of required fleet size, load factor, minimum headway, travel time changes and waiting time, under various design and operational parameters such as passenger arrival patterns, vehicle capacity, reservation time and frequency of departures. The rail DRT model was capable of handling larger networks than Anderson's AGT model and it encompassed a larger variety of output parameters. Although the model's limits were not explored, it successfully solved a network of 26 stations and over 700 vehicles. Again, major restriction was the absence of an objective function or optimization.

2.4 Overview of rail DRT modelling options

Considering typical passenger volumes in heavy rail networks, one can comfortably assume that it requires a vast fleet of vehicles to operate rail DRT as a substitute for scheduled heavy rail. Modelling a rail DRT system can be done from multiple scopes. At microscopic level, each individual vehicle is considered separately. Conversely, in a macroscopic scope, the system is studied at a more aggregate level. Flows of passengers or vehicles are considered rather than individual entities.

An approach to modelling rail DRT microscopically as a variant of the dial-a-ride problem is discussed in section 2.4.1. A closely related, less optimal, but simpler method is ruled-based assignment. This is the topic of section 2.4.2. A macroscopic approach is presented in section 2.4.3. Each of the three sections briefly discuss the modelling concept and then reflect on it referring to relevant literature. Main challenge in any approach is that modelling DRT requires a dynamic and adaptive system representation, whereas fixed timetables are a comfortable and known cornerstone in conventional railway models.

2.4.1 Rail DRT as a special case of the dial-a-ride problem

A key aspect in a rail DRT system at microscopic level is vehicle routing. Passenger waiting time and in-vehicle time are directly related to the system's ability of sending the right vehicle to the correct destination at the proper time moment. The system has to satisfy operational constraints such as service time windows for each request, ride time limitations and vehicle capacity. Hence, modelling the operations of a rail DRT system can be considered a special case of the vehicle routing problem; to be more specific, a dial-a-ride problem (DARP).

Concerning DARPs, most work has been done in the field of 'static' problems rather than 'dynamic' problems. In the static case, all passenger requests are known before vehicle assignment commences. In the dynamic case, some requests are known a priori, while others only become available during vehicle assignment. Depending on the reservation time (the minimum time between desired pick-up time and the moment at which the request must be known at the operator), the dynamic or static case is better applicable to reality. Naturally, the static case fits better with longer reservation time.

In comparison to traditional DARP applications, a DRT passenger rail network has very high ridership with a finite set of origin and destination locations (stations). Furthermore, several additional constraints apply, including restricted route choice due to network characteristics, infeasibility of overtaking dwelling vehicles at some stations and limited node and link capacity. However, the main challenge is related to a DARP's incapability of handling large networks.

The dial-a-ride problem has first been introduced by Wilson et. al. (1971). The earliest studies sought real-time solutions to the dynamic DARP. After that, most focus was on single vehicle, static DARPs. While a single vehicle DARP is by no means representative for rail DRT, the interesting aspect of the first studies into this topic show that exact solutions can only be found for very small systems with the number of requests $n < 10$ (Psaraftis, 1980). From then, most effort has been put into solving the DARP heuristically. The first large study into multi-vehicle DARP was done by Jaw et. al. (1986). In more recent years, focus has been on developing better heuristics for solving the DARP for an increasing number of users and vehicles. Madsen et. al. (1995) updated the work by Jaw and applied it to n=2617 with 28 vehicles. Later studies even went up to n=3000. Nevertheless, this number does not come close to the passenger volumes transported by rail. If DARP methodology is to be applied for the rail DRT problem, there must be a solution to deal with the passenger volumes and fleet size.

2.4.2 Rule-based models and agent-based approaches

The complexity and difficulty of handling large networks when using DARP methodology to model rail DRT can be omitted using a rule-based model. Both a macro- and microscopic approach are possible. A rule-based model relies on a set of predefined steps that can be applied in real-time rather than solving a network-wide optimization problem. Azibi & Vanderpooten (2002) emphasize: "Indeed, rules are quite simple to understand and express." However, while omitting complexity in applying the model, there is increased difficulty in setting up the model and defining all steps and rules. Azibi & Vanderpooten (2002) explain: "Generating these rules is sometimes rather difficult. Moreover, the logical consistency of a rule-based model is more difficult to check than for an analytical model."

In particular the last statement is an important consideration when assessing usability of a rule-based model. Recall that the operational interest of this thesis is to study infrastructure and fleet investments needed for rail DRT. Finding an optimal solution is, to a much greater extent than in the earlier discussed work by Anderson (1998) and Haverkamp & Maat (2015), a key factor in drawing relevant conclusions. One may question if a rule-based model is capable for this purpose. In addition, while being well suited for vehicle or passenger assignment purposes, rule-based models are expected to be challenging to implement for the infrastructure aspect of the research question.

Rule-based assignment does provide an advantage during simulation, because it well suits agent-based programming. A rail DRT system which is composed of swarming vehicles can intuitively be represented by agents. Applying agent-based simulation for DRT systems in general has only very recently become more popular. Cich et. al. (2016) used an agent-based simulation to study the effectiveness of various dispatching strategies in DRT systems. However, their focus was on 'thin flow' networks only, quite the opposite of rail DRT. Ronald et. al. (2015) listed all known agent-based approaches for modelling flexible transport services, such as shared taxis, ridesharing and carpooling. They concluded that it is "still a developing technique".

A challenge is to ensure that agent behaviour is such that a system optimum solution is achieved. User equilibrium is more intuitive in an agent based simulation. However, when assuming a single operator on the railway network, the vehicles will run according to a system optimum for this operator. This phenomenon is discussed in more detail in chapter 3, section 3.4.1.

2.4.3 The rail DRT problem as a network flow problem

At macroscopic level, modelling a rail DRT system could be considered equivalent to a network flow problem; to be more specific, a minimum-cost transhipment problem. Such a problem has been defined compactly and elegantly in its most fundamental form by Le Blanc, Morlok & Pierskalla (1975).

They considered a network with p sets of demand, each having an origin, destination and demand size. These are captured in a matrix P (comparable to an OD-matrix). In addition to the supply and demand locations, there may be extra nodes in the network which do not have supply or demand related to them. Instead they are locations of merging or diverging arcs. There is an arc set A which defines all available arcs between the nodes in the network. Attached to each arc a is a cost r_a for unit transhipment along that arc. The cost is defined as a function of the flow on the arc $r_a = f_a(x_a)$. The problem aims to find the flow $\left(x_a^d\right)$ on each arc a, specified by destination d, such as to minimize total costs while satisfying all demand. The problem is shown schematically in table 2.1.

Traditionally, Le Blanc, Morlok & Pierskalla included 'multi-commodity' flow. When omitting travel classes, the rail DRT problem reduces to single commodity. This is considered sufficiently accurate for the purposes of the research. Le Blanc, Morlok & Pieskalla focussed on solution methodologies for the minimum-cost transhipment problem. Advances in computer technology reduces the relevance of their efforts. Nevertheless, their formulation of the minimum-cost transhipment problem provides a solid basis to expand the transhipment problem into a rail DRT model. Creating a new model from the basic minimum-cost transhipment problem is common practice in other fields, such as in airline scheduling, computer technology and employee rostering.

Minimum-cost transhipment problem

Table 2.1a: Decision variables.

D1	Flow on arc a with destination d	x_a^d

Table 2.1b: Available parameters and sets.

S1	Set of all nodes in the network	$N = [1,2,\dots,n]$
S2	Set of available arcs in the network	$A = [(i,j)_1, (i,j)_2, \dots, (i,j)_l]$
P1	Cost of transhipment of one unit of flow along arc a	$r_a = f_a(x_a)$
P2	OD-matrix	P

Table 2.1c: Derived parameters and sets.

S11	Set of nodes which are a demand point (subset of S1)	$D = \left[q_1, q_2, \dots, q_p\right]$

Table 2.1d: Objective function definition.

OF	$\min\left(\sum_A x_a \cdot r_a\right)$

Table 2.1e: Constraints.

C1	Flow combination	$x_a = \sum_{d \in D} x_a^d$,	$\forall\ a \in A$
C2	Travel cost per arc relates to the flow on the arc	$r_a = f_a(x_a)$,	$\forall\ a \in A$
C3	Flow cannot be negative.	$x_a^d \geq 0$,	$\forall\ a \in A$ $\forall\ d \in D$
C4	Flow continuity: At each node j, the total flow into the node with destination d plus the flow from j to d equals the total outbound flow to d.	$P(j,d) + \sum_i x_{(i,j)}^d = \sum_k x_{(j,k)}^d$,	$\forall\ j \in N$ $j \neq d$ $\forall\ d \in D$

Note that C4 also ensures that all demand is served.

3. Model specifications and development

Chapter 1 stated that model development can be considered the core element in this master thesis project. The following chapter is devoted to that core topic. First, section 3.1 states and justifies the modelling methodology, using information from the literature study. Section 3.2 describes the model's objective. The modelling framework and corresponding definitions are explained in section 3.3. Transition from general modelling methodology to rail DRT model is discussed in section 3.4. Finally, section 3.5 focusses on details and specifications. An overview of the rail DRT model is provided in section 3.6.

3.1 Model methodology

In the literature study, three alternative approaches to the rail DRT modelling problem were proposed: considering rail DRT as a dial-a-ride problem (microscopic), using rule-based modelling (micro- or macroscopic) and reformulating the minimum-cost transhipment problem (macroscopic). The latter option has been selected as the preferred methodology.

The major challenge in selecting a model for rail DRT is the absence of reference material in the field. Nevertheless, some past experiences still are valuable in decision making. The 2015 research by Haverkamp & Maat used a microscopic, rule-based model. The approach was straight-forward and easy to apply. However, the model's microscopic nature created pseudo-accuracy in the results. Any small change in input data resulted in vastly different output. When assessing infrastructure capacity (a strategic level decision), highly detailed vehicle departure times or passenger allocation (an operational level decision) is not required. Rather than knowing the exact moment of departure of every individual vehicle, an insight into flows of vehicles across the rail network offers sufficient insight to assess infrastructure capacity needs.

In addition to the problem of pseudo-accuracy, some microscopic models may pose difficulties in handling large scale networks. The literature study illustrated this issue when using dial-a-ride-methodology to model rail DRT. Considering the disadvantages of pseudo-accuracy and the incapability of handling large scale networks; and taking into account that microscopic data is not strictly required, a macroscopic rail DRT model is preferred.

Rule-based modelling is quickly omitted as well. A major limitation of the 2015 research by Haverkamp & Maat was the absence of optimization or an objective function. It was stated explicitly in the introductory chapter that this issue must be resolved in this thesis. In rule-based assignment it is difficult, if not impossible, to prove that a solution is the optimal solution (Azibi & Vanderpooten, 2002).

Excluding dial-a-ride methodology and rule-based modelling from the earlier proposed approaches, the preferred modelling technique for rail DRT in this thesis is an adaption of the minimum-cost transhipment problem. Figure 3.1 summarizes the main arguments in the model selection process.

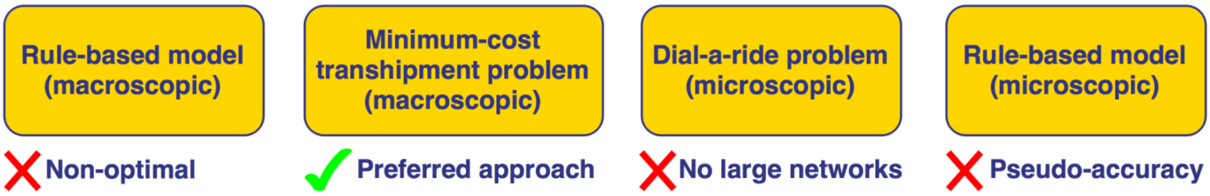


Figure 3.1: Model choice and main arguments.

3.2. Model objective

Recall the thesis' operational interest of providing results which are valuable to NS for assessing infrastructure and fleet investments to operate a rail DRT system at an acceptable level of service. This operational interest shall be reflected by the model objective.

A first suggestion for an objective is to 'minimize infrastructure capacity costs whilst satisfying operational constraints'. This objective seeks the minimum infrastructure capacity needed to operate rail DRT at a specific level of service. An alternative formulation would be to minimize costs of adding or removing infrastructure capacity with respect to the initial infrastructure. However, this suggestion is disregarded. Implementation of new technology for rail DRT (such as a signalling and control system) is expected to require significant changes in infrastructure. There is no benefit in defining the costs of adding or removing infrastructure capacity, because all existing infrastructure needs adaptions anyhow.

The first objective proposal is redefined slightly to allow for a broader spectrum of cost components to be taken into account. Henceforth the model is able to trade-off capacity costs with respect to other factors. Common practise is to identify four major cost components in rail cost-benefit analyses: infrastructure investments, infrastructure maintenance, operational costs and travel time costs. Infrastructure maintenance will be included in the operational costs. NS pays a fee to ProRail for using rail infrastructure. NS considers this fee as part of their operational costs. Therefore, three components remain: infrastructure investments, operational costs and travel time costs. These will be the elements in the objective function. The model will aim to minimize the cumulative value.

objective

Minimize the cumulative value of infrastructure investments, operational costs and travel time costs, whilst satisfying operational constraints.

Satisfying the scientific interest of exploring the unknown field of rail DRT and studying the relations mentioned in the research question is achieved by modelling various scenarios. Scenario design is addressed in detail in chapter 5. At this stage, it is sufficient to assume that fictional networks (numerical application) as well as an existing rail network (practical application) will be assessed. The former is useful for studying the relations mentioned in the main research question. The latter has the additional purpose of providing useful insights for NS.

3.3 Model framework and definitions

Recall the research question from chapter 1. Seven aspects were mentioned: network structure, passenger demand distribution, station platform capacity, track capacity, fleet size, level of service and offered seat kilometres. The following sections describe and specify several of these seven aspects in closer detail. Some are combined into a single section, whilst there are additional paragraphs to discuss other considerations. The sub-chapter concludes with a list of model requirements and an overview of the model's main elements.

3.3.1 Network structure and stations

Starting point is a certain network represented by a graph of nodes and arcs. Every station and every junction is a separate node. The network structure is fixed. That is, while no new arcs or nodes may be added, the capacity of existing nodes and arcs can be adapted to find the optimal solution for operating the DRT system. Every node and arc is assigned an initial capacity (not necessarily integer numbers). Furthermore, every arc has a free speed associated with it. During optimization, arc capacity may be set to zero. In that case, the optimal solution apparently does not require that link to exist and it could be removed from the network. Conversely, there will be no suggestions for adding new links to possibly create a more efficient network. The scope is limited to assessing the network structure like it is.

In the fictional networks, initial capacity and free speed may be set according to preference. In the case study, the parameters must correspond to reality. One could pose the question if the current situation in the case study must be a lower bound (no reduction of infrastructure possible) or not. The model objective formulation actually answers this question implicitly. In section 3.2 it was argued that the costs of total infrastructure capacity is favoured over the costs of adding or removing infrastructure. This implies that existing infrastructure capacity need not be included as a lower bound constraint. Else, the constraint would counteract the objective formulation.

3.3.2 Passenger demand distribution

In case of a fictional network, some travel demand must be specified. In the case study, the most recent data is used. In the introductory chapter it was already identified that an OD-matrix should be available for various time of day. The OD-matrix is assumed to be uniform over a specified time frame. The length of the time frame is topic of discussion in chapter 6 on scenario design. The model must be able to handle varying demand. That is, the OD-matrix in one time frame may be different from the next. It is assumed that the OD-matrix is fully known a-priori. Effects of reservation time have already been studied in the 2015 exploratory study by Haverkamp & Maat.

Travel behaviour and trip patterns will change as a result of introducing DRT. Currently, stations served by intercity trains are more attractive than those served by sprinters only. In a DRT system, any station is equally attractive in terms of transport service offered. This is based on the assumption that every passenger request in a rail DRT system is handled similarly, regardless of a customer's origin, destination or moment of departure. The current difference in transportation service attractiveness between intercity stations and sprinter stations diminishes.

The most probable consequence of levelling service attractiveness is an increasing tendency of passengers choosing their origin and destination station based on the vicinity to their place of activity or home rather than on station service attractiveness. Stations´ spheres of influence will grow into more uniformly sized areas. Current sprinter stations will experience passenger growth, while intercity stations may see a (relative) decline.

In addition to changes in travel behaviour and trip patterns of existing passengers, there may also be a change in ridership itself. A rule of thumb in transportation theory is a negative elasticity between travel time and ridership. Therefore, if rail DRT offers different travel times compared to the current supply driven system, passenger numbers will change accordingly.

Ultimately, the two aforementioned factors of changing travel demand could be topic of an entire thesis on its own. For the purposes of the current research, it is assumed justifiable to use today's data when assessing existing networks. In the fictional networks, various demand scenarios could be defined to study rail DRT sensitivity to changing ridership. This will be discussed in chapter 5.

Finally, a challenge arises when the existing network scenario considers just a part of an existing network. For example, the northern part of an existing network is changed into DRT, while the southern part remains supply driven. If there are multiple stations where the DRT network and supply driven network connect, one must assume a certain transfer station between DRT and supply driven system for every passenger with an origin in one area and a destination in the other. Depending on the quantity of transferring passengers, these assumptions may have profound consequences for the flows of passengers and vehicles in the system. Also, the aspect of having a transfer penalty needs consideration. A final decision on this issue will be made in chapter 6, based on available data.

3.3.3 *Rolling stock and signalling & control*

Common limitations imposed by signalling and control systems, like minimum headway, are assumed not to apply to the rail DRT system. Autonomous vehicles deployed in rail DRT can operate at any headway and are assumed to have an automatic train operation system in place. In future studies, advances in vehicle technology research may impose new restrictions and limitations. For now, it is assumed that all vehicles in the network are capable of running at the maximum allowed speed and at any headway. Acceleration properties and dwell time are in line with common standards for vehicles of the chosen size. This will be discussed in detail in chapter 5.

The autonomous nature of the DRT vehicles must be considered when analysing track and station capacity. Studies in the field of autonomous road vehicles on platooning and vehicle interaction may be of interest. This is elaborated upon in chapter 5.

3.3.4 *Perturbing elements*

It is arguable whether or not to include bridges, grade crossings, junctions and other potentially timetable-perturbing elements in the rail DRT model. Disregarding these elements was identified as a potential source of error in the 2015 exploratory research by Haverkamp & Maat. Nevertheless, it appears out of balance to enforce that existing perturbing elements may not be removed in far future, while simultaneously the rail DRT model has the freedom to expand or decrease capacity of all nodes and links. Therefore, considering that this research is at strategic level compared to the 2015 study at operational level, it is assumed justifiable to neglect perturbing elements altogether.

3.3.4 *Model framework overview*

All of the definitions discussed in the precursory sections are combined in figure 3.2. It shows the model framework, including input, output, objective and scope boundaries.

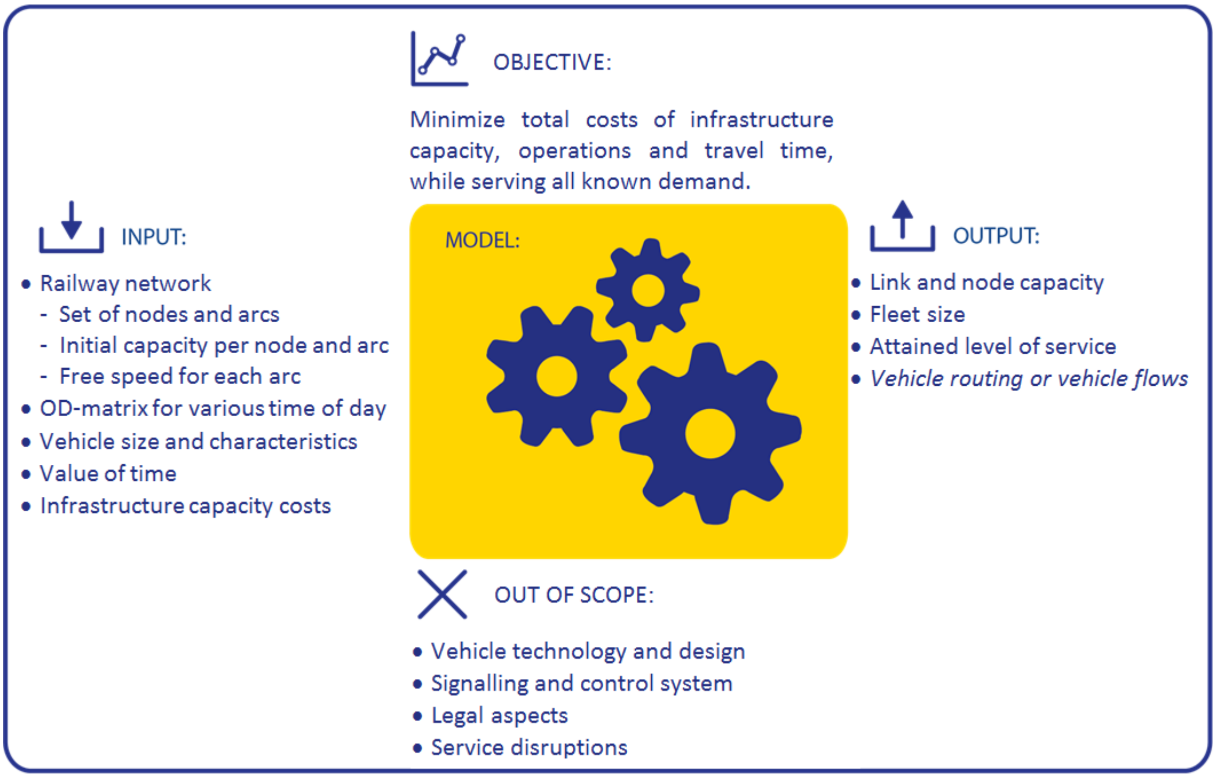


Figure 3.2: Model framework.

In addition to figure 3.2, the following list of model requirements hold. The indicated numbers are based upon the 2015 case study by Haverkamp & Maat. The model in this thesis must be capable of handling at least a similarly sized subnetwork as the 2015 research in terms of acceptable running time:

- Be able to handle at least 35,000 passenger requests per hour.
- Be able to handle networks of different sizes; at least 30 nodes and 60 arcs.
- The solution need not be exact. It may be achieved through heuristics as well.

3.4 Model development: transition from flow problem to rail DRT problem

The minimum-cost transhipment problem has been introduced in chapter 2. The basic set-up must now be extended for application to rail DRT. Most existing applications of the minimum-cost transhipment problem to date have been in the field of road transport. The following sections describe the transition to rail DRT application. It is assumed that the reader is familiar with the basic concept of the minimum-cost transhipment problem.

3.4.1 Intermezzo: system optimum versus user equilibrium

The minimum-cost transhipment problem is not limited to road bound cases. In fact, a common difficulty in road applications is quickly omitted in rail. Individual road users tend to choose their route such that they experience lowest costs. In a perfect settled case, a change in route choice for any of the drivers will increase their individual travel cost. This is an equilibrium flow situation. Stewart (1979) states: “the equilibrium flow in the network is in general different from the system optimal flow.” Consider a case where there is major congestion. If part of the drivers divert and hence increase their own travel cost, the congestion on the major road resolves, which cumulatively decreases travel cost for the system as a whole. The situation with lowest total costs is the system optimum solution.

Put short, a system optimum might be disadvantageous for some individual users. Therefore, it is hard to realize in road traffic where all drivers are free to choose their route. In a rail DRT network all vehicles are controlled by some central intelligence, allowing system optimal solutions to be achieved, because the system may send specific vehicles along higher cost routes, gaining benefits elsewhere in the system and hence reducing overall costs. One could even have passengers pay additional fees for service guarantee. They will pay to ensure that their vehicle takes the shortest route. However, such options are beyond the scope of this study. For now, it suffices to assume that a system optimal model can be applied to rail DRT.

A user equilibrium may be of interest if different vehicles in the rail DRT system are deployed by different operators. In that scenario, each company wants to operate their own vehicles at minimum costs, which may not be the system optimal. However, given that this research is conducted on behalf of NS, which holds the exclusive rights to operate the main line network, a system optimum case is better applicable. Naturally, one could pose the question if NS still holds the exclusive rights at the time when a rail DRT system is in operation. Nevertheless, such question is beyond the scope of this research.

3.4.2 Basic minimum-cost transhipment problem redefinition for future use

Before implementing the redefined objective function, the basic minimum-cost transhipment problem is adapted to allow for future extensions more easily. In the adapted problem definition, flow distinction per OD-pair replaces flow distinction per destination only. This enables calculations which require knowledge on the routing of flows. Also, the OD-distinction eases visualization of results.

Simply replacing 'D' by 'OD' does not suffice. In the 'OD-case', constraint C4 must hold for every unique OD-pair, in similar analogy to the traditional constraint holding for every unique destination. If 'D' in C4 would simply be replaced by 'OD' $\left((j,d) + \sum_i \sum_O x_{(i,j)}^{(o,d)} = \sum_k \sum_O x_{(j,k)}^{(o,d)}\right)$, it would result in an inconsistent notation. The correct redefinition of C4 is a decomposition into three constraints.

<u>*Minimum-cost transhipment problem with distinction of flow per OD-pair*</u>

Table 3.1a: Decision variables.

D1	Flow on arc a originating at o having destination d	$x_a^{(o,d)}$

Table 3.1b: Available input parameters and sets.

S1	Set of all nodes in the network	$N = [1,2,\dots,n]$
S2	Set of available arcs in the network	$A = [(i,j)_1,(i,j)_2,\dots,(i,j)_l]$
P1	Cost of transhipment of one unit of flow along the arc a	$r_a = f_a(x_a)$
P2	OD-matrix	P

Table 3.1c: Derived parameters and sets.

S12	Set of OD-pairs	$OD = [(o,d)_1,(o,d)_2,\dots,(o,d)_b]$

Table 3.1d: Objective function definition.

OF	$\min\left(\sum_A x_a \cdot r_a\right)$

Table 3.1e: Constraints.

C1	Flow combination	$x_a = \sum_{(o,d)\in OD} x_a^{(o,d)}$,	$\forall\, a \in A$
C2	Travel cost per arc relates to the flow on the arc	$r_a = f_a(x_a)$,	$\forall\, a \in A$
C3	Flow cannot be negative	$x_a^{(o,d)} \geq 0$,	$\forall\, a \in A$ $\forall\, (o,d) \in OD$
C4.1	Flow continuity at all intermediate nodes j	$\sum_i x_{(i,j)}^{(o,d)} = \sum_k x_{(j,k)}^{(o,d)}$,	$\forall (o,d) \in OD$ $\forall\, j \in N$ $j \neq d \,\&\, j \neq o$
C4.2	Demand satisfaction at origin	$\sum_k x_{(o,k)}^{(o,d)} = P(o,d)$,	$\forall\, (o,d) \in OD$
C4.3	Demand satisfaction at destination	$\sum_i x_{(i,d)}^{(o,d)} = P(o,d)$,	$\forall\, (o,d) \in OD$

3.4.3 *Adjusted objective function and new decision variables*

The next step in developing the rail DRT model is to change the transhipment problem's traditional objective function into the rail DRT objective function defined in section 3.2. In practical terms, the rail DRT objective is a trade-off between the costs of adding infrastructure capacity, and the costs of delay or detours when not adding this infrastructure capacity. The objective raises two questions concerning its implementation. First, how to define the cost components? Second, how to create a representative weighted sum of the cost components? Assuming that all cost components can be expressed in monetary units, there is no need to have multi-objective optimization or weight factors.

Level of service must be incorporated in the model too. For passengers, the performance indicator which is directly related to level of service is travel time including (weighted) waiting time. Therefore, the link travel cost functions in the traditional transhipment problem definition are replaced by link travel time functions. The exact definition of those functions is topic of later study in section 3.5. For now, it suffices to assume that there exists a function which relates both link and node capacity to travel time, given a certain flow. Note that additional constraints (C5 and C6) are required to restrict the model to positive infrastructure capacity.

In chapter 1 it was argued that level of service shall not be included as a hard constraint to prevent problems arising from infeasible solutions. The model objective ensures a monetary balance between the three cost components such that the cumulative cost value is minimized. The inclusion of passenger costs in the objective function acts like a level of service constraint. The model cannot accept lengthy trips because it will increase travel time costs. However, individual passengers may experience extreme travel time or waiting time changes, because the model only considers total travel time costs. Nevertheless, output of the model is the attained level of service (travel time and waiting time) and the operator judges this level of service to be acceptable or not. Adaptions can be made to the objective function’s weighting factors or to the travel time definition in case of too little emphasis on level of service.

3.4.4 The infrastructure capacity trade-off problem

Implementing the changes and assumptions mentioned in section 3.4.3, yields the following infrastructure capacity trade-off problem:

Infrastructure capacity trade-off problem

Table 3.2a: Decision variables.

D1	Flow on arc a originating at o having destination d	$x_a^{(o,d)}$
D2	Capacity of arc a	c_a
D3	Capacity of node j	s_j

Table 3.2b: Available parameters and sets.

S1	Set of all nodes in the network	$N = [1,2,\dots,n]$
S2	Set of available arcs in the network	$A = [(i,j)_1,(i,j)_2,\dots,(i,j)_l]$
P1	Cost of transhipment of one unit of flow along arc a	$r_a = f_a(x_a,c_a,s_j)$
P2	OD-matrix	P
P3	Link capacity weight factor	w_1
P4	Node capacity weight factor	w_2
P5	Operational costs weight factor	w_3
P6	Travel time costs weight factor	w_4

Table 3.2c: Derived parameters and sets.

S12	Set of OD-pairs	$OD = [(o,d)_1,(o,d)_2,\dots,(o,d)_b]$

Table 3.2d: Objective function definition.

OF	$\min\left(\sum_A w_1 \cdot c_a + \sum_N w_2 \cdot s_j\right) + w_3 \cdot operational\ costs + w_4 \cdot travel\ time\ costs$

Table 3.2e: Constraints.

C1	Flow combination	$x_a = \sum_{(o,d) \in OD} x_a^{(o,d)}$,	$\forall\, a \in A$
C2	Travel cost per arc relates to the flow on the arc	$r_a = f_a(x_a, c_a, s_i)$,	$\forall\, a \in A$
C3	Flow cannot be negative	$x_a^{(o,d)} \geq 0$,	$\forall\, a \in A$ $\forall\, (o,d) \in OD$
C4.1	Flow continuity at all intermediate nodes j	$\sum_i x_{(i,j)}^{(o,d)} = \sum_k x_{(j,k)}^{(o,d)}$,	$\forall\, (o,d) \in OD$ $\forall\, j \in N$ $j \neq d \,\&\, j \neq o$
C4.2	Demand satisfaction at origin	$\sum_k x_{(o,k)}^{(o,d)} = P(o,d)$,	$\forall\, (o,d) \in OD$
C4.3	Demand satisfaction at destination	$\sum_i x_{(i,d)}^{(o,d)} = P(o,d)$,	$\forall\, (o,d) \in OD$
C5	Link capacity cannot be negative	$c_a \geq 0$,	$\forall\, a \in A$
C6	Node capacity cannot be negative	$s_j \geq 0$,	$\forall\, j \in N$

Solving the infrastructure capacity trade-off problem will provide the flows on each arc in the network, as well as the capacity of each arc and node. There are some fundamental assumptions enclosed in the model formulation, which need closer attention before using the results.

The output parameter of flow in the model is expressed in the same units as the input OD-matrix. Naturally, one would expect an OD-matrix to include passenger numbers, while flows are expressed in vehicles per time unit. Therefore, some conversion is needed. This is discussed in section 3.5.3.

Another fundamental assumption is that all demand in the OD-matrix is served directly and non-stop. This is enforced by constraints C4.1, C4.2 and C4.3. In practise, for the sake of efficiency, one would expect vehicles to make intermediate stops if there is demand from or to that intermediate node, sufficient vehicle capacity is available and level of service thresholds are still satisfied. There are two options: either holding on to the assumption and listing it as a deficiency of the model or make adaptions to the model to resolve the issue. This is elaborated upon in section 3.5.3.

3.5 Model details and specifications

The infrastructure capacity trade-off model presented in table 3.2 is the basis for the rail DRT model. The following sections focus on specific aspects of the model, such as the travel time function in constraint C2, passenger and vehicle costs, units of input data and additional considerations.

3.5.1 Arc speed-density relation

There has been very limited (scientific) research into the relation between infrastructure capacity, train traffic intensity and delays. Most studies are limited to time-table robustness analysis. For roads there is a 1000 page Highway Capacity Manual. The rail counterpart has been proposed in 2004 as the UIC Capacity Handbook. It contains 26 pages and is rather limited in level of detail. Nevertheless, it provides some useful guidelines. The Handbook suggests that capacity utilization should be lower than approximately 60 to 70% on a daily basis to ensure robust operations. During peak hours, the upper bound is 75 to 80%. Although these numbers are based on compression analysis using traditional block signalling systems, they can be used as a starting point for the novel rail DRT system.

Featuring autonomous vehicles running at short headways, a rail DRT system shows commonalities with autonomously driving cars. Considering the lack of rail DRT reference material, the speed-density relation for rail DRT vehicles is based on autonomously driving car theories. The fundamental diagram is the basis of traditional traffic flow theory. Kerner (2015) identified that classical theories lead to erroneous results in highly automated systems. Rather than the conventional 'smooth and gradual' fundamental curve, the flow-density diagram corresponding to platooning vehicles has an abrupt transition into congestion around some critical flow density. Correspondingly, the speed density function is a logistic relation with an abrupt transition from free flow to jam. A comparable logistic speed-density relation is assumed to apply to rail DRT vehicles.

Let V_a be the speed of vehicles running along arc a. The arc has been assigned a fixed free speed $V_{a_{free}}$. Then, V_a can be expressed in terms of free speed $V_{a_{free}}$ and speed reduction factor f_{v_a} according to equation 3-1. Travel time r_a on an arc is related to the attained speed. Acceleration and deceleration loss are included later in the node delay function.

$$V_a = V_{a_{free}} \cdot f_{v_a} \tag{3-1a}$$

$$f_{v_a} = \frac{1}{1 + e^{-\alpha \cdot (\varphi_a - \beta)}} \tag{3-1b}$$

$$\varphi_a = \frac{x_a}{y \cdot c_a} \tag{3-1c}$$

$$r_a = \frac{L_a}{V_a} \tag{3-2}$$

The parameters α and β scale and shift the logistic function. Their values are determined during scenario development in chapter 5, using the aforementioned UIC advise on capacity utilization and considering the relative abrupt nature of the logistic speed-density relation in autonomous systems.

3.5.2 Node delay-density relation

Likewise to the arc speed-density function, a relation is assumed to exist between vehicle flow through a node, the capacity of the node and the delay experienced. In practical terms, a vehicle will suffer from delay if there are no free platforms available upon arrival at a station. There is a higher chance of experiencing delay when the vehicle flow into a node increases and the available capacity does not grow accordingly (more delay at higher density). Strictly speaking, the node delay-density relation should therefore include a probability of experiencing a delay of some severity. This is an example of queuing theory. However, in a DRT system with frequent services, it may be justifiable to add a density-dependent delay to each vehicle based on a predefined function. The following section describes both options and justifies the choice of queuing theory over a pre-defined delay function.

The function which is assumed most appropriate to relate density to delay is an exponential function. In case of light traffic, there is hardly any chance of the station being 'full'. In that case, delays are caused only by conflicts at the junction into the station. Once traffic rate increases, both the number of conflicts at the junction and the number of occasions in which the station is 'full' will grow. Handling a flow beyond capacity limits should theoretically lead to infinite waiting times, because the queue of vehicles wishing to enter the station grows faster than the rate at which it can be resolved. These effects are captured by an exponential function which starts close to zero and approaches infinity in the limit.

One could argue that a vehicle may also experience delay upon leaving a node, for example because it needs to wait for a free space in a platoon of vehicles driving on an arc. Nevertheless, for simplicity purposes, both delay upon arrival and departure are assumed to be represented by one single exponential delay-density function.

A vehicle which does not call at a station experiences delay if there is no opportunity to overtake dwelling vehicles. In current-day timetabling, this effect is very prominent. Capacity utilization is much higher in systems of homogeneous service compared to heterogeneous alternatives. A rail DRT system is highly heterogeneous. However, the resulting effect on capacity is not captured by the suggested exponential delay-density relation. When determining capacity utilization, it does not distinguish between dwelling and non-stop vehicles. This is the method's biggest shortcoming.

An alternative formulation of node delay, which resolves the aforementioned issue, is provided by queueing theory. It is a generally applicable method which determines the waiting time between a service request and the actual start of service. Its range of applications is vast: from computer technology to grocery store design. The following sections describe how queuing theory is used to model rail DRT.

A vehicle can either call at a node or drive through without stopping. In either case, the vehicle must be 'served' by node. In more practical terms: there must be space available for the vehicle to enter the station and make a call or drive through. If no space is available, the vehicle will queue in front of the station (a queue of 'service requests'). The queue is handled on a first-come-first-serve basis except for prioritized vehicles, which are served as soon as possible.

Consider the arrivals of vehicles on each unique OD-pair into a node as a Poisson process. The assumption of Poisson distributed arrivals is justified by the expected high frequency of services and the stochastic nature of the delay induced along the route. In similar analogy, assume a Poisson process for departures of vehicles which originate at the node of interest. The latter group may not be omitted, because that would result in too optimistic platform occupancy, in particular at termini. Let $x_j^{(o,d)}$ denote the number of arrivals per hour of a specific OD-pair into node j or the number of hourly departures of vehicles originating at node j. This definition is shown explicitly by equation 3-3. The corresponding probability density function of hourly service request of vehicles on OD-pair (o,d) at node j is described by equation 3.4.

$$x_j^{(o,d)} = \begin{cases} P(o,d) & if\ j = o \\ P(o,d) & if\ j = d \\ \sum_i x_{(i,j)}^{(o,d)} & if\ j \neq o\ and\ j \neq d \end{cases} \qquad 3\text{-}3$$

$$P\left(Y_j^{(o,d)} = g\right) = \frac{\lambda^g \cdot e^{-\lambda}}{g!}, \quad where \quad \lambda = x_j^{(o,d)} \qquad 3\text{-}4$$

The additive property of a Poisson process implies that the service requests of all vehicles at a node may be considered a single Poisson process with event rate parameter λ_j according to equation 3-5.

$$\lambda_j = \sum_{(o,d)\in OD} x_j^{(o,d)} \qquad 3\text{-}5$$

Extensive scientific research has been conducted into queuing theory. Most studies focus on specific cases in terms of service properties. Therefore, existing queuing theory can be applied to rail DRT, provided that the service properties and queuing characteristics are well defined.

Note that most stations are multidirectional, meaning that vehicles can depart in at least two distinct directions. In a graph representation, a multidirectional station is a node with at least two incoming and two outgoing arcs. In practise, there could be a queue on each of the incoming arcs. Every vehicle which enters one of the queues is labelled with a time stamp. Once a platform is available, the vehicle with the earliest time stamp is served, regardless of which queue the vehicle is in. For modelling purposes, the multiple physical queues can therefore be treated as a single queue on the condition that all platforms are accessible from any queue.

Consider a node in the network. Denote all vehicles which make a call as 'class 2'. Vehicles which do not call at the node are 'class 1'. If the node is a station with more than two platforms, it is assumed that through-going vehicles (class 1) can overtake dwelling vehicles (class 2) in the queue and in the station. Hence, class 1 has priority over class 2 at stations with more than two platforms ($s_{prio} = 3$). Stations with fewer platforms do not offer overtaking possibility, hence eliminating any prioritizing.

At nodes with prioritizing, the queueing system is non-pre-emptive. This means that a vehicle which is currently being serviced, is allowed to finish its service without interruption. In practise, this means that a vehicle which dwells at a platform will only clear the platform once it finishes (off)loading passengers. Naturally, the service will not be interrupted when a higher class vehicle arrives at the queue, because a vehicle cannot be removed from the platform while passengers are (dis)embarking.

Considering each platform a 'server' and assuming that all vehicles have the same mean service time $1/\mu_j$ with an exponential service time distribution and all vehicles can use all platforms, the DRT station is characterized as a non-pre-emptive M/M/c system according to Kendall's standard notation for queuing theory. However, class 1 vehicles have very short service time, while it is the sum of acceleration loss, deceleration loss, dwell time and switch setting time for class 2 vehicles. Formally, this would require a model with a different mean service time per priority class. Such a model is highly complex and has only recently become of interest in scientific papers. No explicit equations exist for cases of more than two servers (Baron, Scheller-Wolf & Wang, 2015). Therefore, a priority-dependent μ_j cannot be applied to this thesis.

The proposed solution to the priority-dependent μ problem is to hold on to the assumption of one single μ_j. Its value is based on the ratio of class 1 to class 2 vehicles (equations 3-6 and 3-7) at the node of interest j. This assumption is justified because queuing theory focusses on waiting time only. For class 2 vehicles, a dwell time t_d shall be added on top of the waiting time. For class 1 vehicles, there is no additional component. Acceleration and deceleration losses are not added separately. They are assumed to be captured by waiting time.

$$\lambda_{j_1} = \sum_{(o,d)\in OD,\ \ o\neq j\ \&d\neq j} x_j^{(o,d)} \tag{3-6a}$$

$$\lambda_{j_2} = \sum_{(o,d)\in OD,\ \ d=j} x_j^{(o,d)} + \sum_{(o,d)\in OD,\ \ o=j} x_j^{(o,d)} \tag{3-6b}$$

$$\frac{1}{\mu_j} = \frac{\sum_{h=1}^{2} \left(\lambda_{j_h}/\mu_h\right)}{\sum_{h=1}^{2} \lambda_{j_h}} \tag{3-7}$$

The expected waiting time in the non-pre-emptive M/M/c queue depends on delay probability Π (Kella & Yechiali, 1985), which is shown in equations 3-8 and 3-9. From the last relation it is clear that s_j must be integer. This constraint must be added to the model.

$$\rho_{j_h} = \frac{\lambda_{j_h}}{s_j \cdot \mu_j} \qquad \text{3-8a}$$

$$\rho_j = \sum_{h=1}^{2} \rho_{j_h} \qquad \text{3-8b}$$

$$\Pi_j = \frac{\left(s_j \cdot \rho_j\right)^{s_j}}{s_j!} \cdot \frac{1}{\frac{\left(s_j \cdot \rho_j\right)^{s_j}}{s_j!} + \left(1-\rho_j\right) \cdot \sum_{m=0}^{s_j-1} \frac{\left(s_j \cdot \rho_j\right)^{m}}{m!}} \qquad \text{3-9}$$

The corresponding expected waiting time in prioritized and non-prioritized queuing systems can now be determined according to equations 3-10a, 3-10b and 3-11 (Wagner, 1997).

$$E\left(W_{j_1}\right) = \frac{1}{s_j \cdot \mu_j \cdot \left(1-\rho_{j_1}\right)} \cdot \Pi_j \qquad \mathit{prioritized, class}\ 1 \qquad \text{3-10a}$$

$$E\left(W_{j_2}\right) = \frac{1}{s_j \cdot \mu_j \cdot \left(1-\rho_{j_2}-\rho_{j_1}\right) \cdot \left(1-\rho_{j_1}\right)} \cdot \Pi_j \qquad \mathit{prioritized, class}\ 2 \qquad \text{3-10b}$$

$$E\left(W_j\right) = \frac{1}{s_j \cdot \mu_j \cdot \left(1-\rho_j\right)} \cdot \Pi_j \qquad \mathit{non\ prioritized} \qquad \text{3-11}$$

Equations 3-10 and 3-11 demonstrate that ρ_j may not exceed a value of 1. In case ρ_j does exceed unity, the model produces erroneous results. Therefore, $\rho_j \leq 1.0$ shall be added as a constraint to the rail DRT model.

3.5.3 *From passenger OD-matrix to vehicle flow*

The infrastructure minimization problem has not yet defined the units of some of the variables. Intuitively, the decision variable of flow (x) is expressed in vehicles per hour. The model's input OD-matrix must then be defined in vehicles per hour as well, because it is used directly and without conversion in the model's objective and constraints. However, OD-matrices are typically expressed in passengers per hour instead. A conversion from passengers to vehicles is required (equation 3-12). This conversion is based on vehicle size and average load factor, under the assumption of a homogenous fleet. The input OD-matrix then represents the number of departures per hour on each OD-pair. Rounding to integer numbers is not required for the theoretical model in this research.

$$v_{(o,d)} = \frac{P(o,d)\left[\frac{passengers}{hour}\right]}{z \cdot \xi} \qquad \text{3-12a}$$

The implication of using a fixed load factor to determine the number of departures per hour is that the DRT system offers direct, non-stop service to everyone. In practise, this is doubtful. Low demand OD-pairs will see infrequent departures, resulting in either unattractive or inefficient services.

Low demand routes could better be served alternatively, for example by adding stops on existing routes, through extending other routes or by introducing transfers. To find the optimal dispatching methodology and operational plan, it is worthwhile to apply an operational model. However, that would be beyond the scope of this thesis.

It is assumed that OD-pairs are not served directly if their passenger demand does not require at least a certain minimum service frequency v_{min}. In that case, passengers are served by the remaining capacity in the vehicles deployed on higher demand routes to and from the origin and destination stations. This may result in transfers for some passengers and additional stops for certain vehicles. In exceptional cases, when demand on all OD-pairs into and out of a specific station is low, that station might not be served at all. Corresponding effects are neglected, because prevalence is expected to be very low. For verification purposes, the model will output the share of unsatisfied demand. The values of v_{min}, z and ξ are discussed in chapter 5 during scenario development.

$$P(o,d)\left[\frac{vehicle\ departures}{hour}\right] = \begin{cases} v_{(o,d)} & if\ v_{(o,d)} \geq v_{min} \\ 0 & if\ v_{(o,d)} < v_{min} \end{cases} \tag{3-12b}$$

An alternative solution to the passenger-vehicle assignment problem is the methodology which is used at NS to relate train-delay and passenger-delay. However, that methodology proved not to be applicable to the rail DRT case, because it is an ex-post method and cannot be used ex-ante for predictive purposes. NS does have predictive models about passenger ridership. However, these are line models, which cover a completely different scope than intended for this thesis.

An additional challenge arises by long distance travel. In train networks, passengers may board a vehicle during rush hour, while they arrive at their destination several hours later during off-peak. The flow induced by their rush hour departure need not be taken into account at links close to the destination at the same time. Else, results could be diluted. Nevertheless, this error is assumed to be negligibly small. An average train trip in The Netherlands takes 38 minutes with a standard deviation of 8 minutes. The share of long distance trips is small, reducing the associated error.

3.5.4 Including passenger costs

Passenger costs are related directly to travel time. However, travel time consists of waiting time and in-vehicle time, each being experienced differently by passengers. In a rail DRT system there is reduced need to plan a journey in advance, because the system must adapt its service according to customer requests. Therefore, it is assumed justifiable to take half the vehicle departure interval as waiting time for all passengers traveling on the OD-pair of interest. The in-vehicle time depends on the vehicle routing and the corresponding values of the speed-density and delay-density functions described in sections 3.5.1 and 3.5.2. Equations 3-13, 3-14 and 3-15 describe the process of determining total in-vehicle time and waiting time for all passengers travelling between an OD-pair.

$$u_j = \begin{cases} 1\ if\ s_j \geq s_{prio} \\ 0\ if\ s_j < s_{prio} \end{cases} \tag{3-13}$$

$$\begin{aligned} T_{veh}^{(o,d)} = & \sum_{a\in A} x_a^{(o,d)} \cdot r_a \cdot z \cdot \xi \\ & + \sum_{(i,j)\in A \ \&\ j\neq d} x_{(i,j)}^{(o,d)} \cdot z \cdot \xi \cdot \left(u_j \cdot E\left(W_{j_1}\right) + (1-u_j) \cdot E(W_j)\right) \\ & + P(o,d) \cdot z \cdot \xi \cdot \left(u_d \cdot E\left(W_{d_2}\right) + (1-u_d) \cdot E(W_d) + t_d\right) \end{aligned} \tag{3-14}$$

$$T_w^{(o,d)} = \frac{1}{2} \cdot \frac{60}{P(o,d)} \cdot P(o,d) \cdot z \cdot \xi = 30 \cdot z \cdot \xi \qquad 3\text{-}15$$

Interestingly, equation 3-15 indicates that total waiting time per OD-pair depends on vehicle size and load factor only. It is independent of the travel demand on that specific OD-pair. This implies that there is no relation between $T_w^{(o,d)}$ and the decision variables in the infrastructure capacity trade-off problem. Therefore, the component of travel time in the problem's objective function is replaced by in-vehicle time only.

Note that the transhipment model may send part of a vehicle flow between A and B via a different route as part of the trade-off between infrastructure capacity costs, operational costs and passenger costs. The implication is a longer travel time for a part of the flow.

In case passengers somehow know that a share of the vehicles takes a longer route, the principle of constant load factor may not hold anymore. This could be modelled by a logit model in which the disutility of travel time determines the distribution of passengers among both routes. However, it is unlikely that passengers are aware of the vehicle route choice. Moreover, if a passenger decides not to board a detouring vehicle, its waiting time will be longer, because it takes another interval for the next vehicle to depart. Therefore, a choice model will not be used and the principle of constant load factor remains.

Passengers costs are computed from travel time using the value of time (VOT) value for an average train passenger. Distinction by customer type, travel motive or other passenger characteristics is not applied. Chapter 5 specifies the choice of VOT.

3.5.5 *Infrastructure costs and related weight factors*

A major question in determining infrastructure costs is the relation between infrastructure costs and capacity. One could assume a certain fixed price for each kilometre of track and for each additional metre of platform length at stations. However, the capacity of one such piece of track or one stretch of platform remains open for debate. Chapter 5 discusses how to obtain a capacity value based on references from autonomous driving and current high frequency railway systems.

The question of assigning a fixed price per kilometre of track and stretch of platform length has been discussed with ProRail. Their advice is to differentiate between underground, elevated and level infrastructure in a 10:3:1 price ratio. Different costs will then apply for different parts of the network. The same advice was given for node capacity. Some stations allow for relatively cheap capacity expansion, while others are very expensive (monumental stations and underground stations). Considering the long term nature of the rail DRT concept and the associated uncertainty of (political) decisions on spatial planning, it is judged unrealistic to include price dependency on infrastructure type. Instead, one common price is used. Chapter 5 presents the values used in various scenarios. These values are converted to an hourly price in order to ensure a fair trade-off in the optimization model between travel time costs and operational costs, both of which are timeframe-related as well. Equation 3-16 describes the corresponding time conversion. Discount factors need not be included.

$$E_1 \left[\frac{€}{km \cdot hr}\right] = \frac{E_1 \left[\frac{€}{km \cdot 30\, yrs}\right]}{30 \cdot 365.25 \cdot 24} \qquad 3\text{-}16a$$

$$E_2 \left[\frac{€}{m \cdot hr}\right] = \frac{E_2 \left[\frac{€}{200m \cdot 30\, yrs}\right]}{200 \cdot 30 \cdot 365.25 \cdot 24} \qquad 3\text{-}16b$$

Station capacity costs are expressed per metre of platform length. The required platform length depends strongly on vehicle size. It is assumed that every platform needs a set of low speed switches. The corresponding platform length will be referred to as the 'fixed platform length component' $L_{p_{fix}}$. The remaining platform length depends on vehicle size. Variable $L_{p_{var}}$ represents the number of seats in a vehicle per metre of platform length. Both components are combined into equation 3-17. Chapter 5 determines the values of $L_{p_{fix}}$ and $L_{p_{var}}$.

$$L_p = L_{p_{fix}} + \frac{z}{L_{p_{var}}} \tag{3-17}$$

3.5.6 *Fleet size*

NS has particular interest in the fleet size required for rail DRT. It offers a valuable indication of the investments needed to operate the system. Although vehicle circulation in the network is an operational question, it is possible to derive an approximation of fleet size from the decision variables in the rail DRT model.

Total travel time among all passengers has been defined on an OD-basis in equation 3-14. Dividing the results by vehicle size and average occupancy yields the amount of vehicle hours deployed on an OD-pair during each hour of operations. In 2015, Haverkamp & Maat concluded that vehicles spend 95% of their time driving on the network, while the remainder is lost at depots. In addition, only 80% of the vehicle hours are used for carrying passengers. One fifth is lost on deadheading and returning to depots. Combining both factors, means that the vehicle hours derived from equation 3-14 must be compensated by a factor $1/(0.95 \cdot 0.8) = 1.32$. The results provide an indication of fleet size for that specific OD-pair. Summing over all OD-pairs represents the entire fleet. The approach is summarized by equation 3-18.

$$F = \sum_{(o,d)\in OD} 1.32 \cdot \frac{T_{veh}^{(o,d)}}{z \cdot \xi} \tag{3-18}$$

Note that the approach to determining fleet size is different from the common method applied in traditional supply driven rail systems. Typically, timetables are symmetric which enables a straight-forward calculation of the time required to operate one train set from A to B and back to A again. It simply is twice the scheduled travel time plus the layover time at both termini. Based on service frequency, one can derive the number of train sets required to operate the line. Efficiency gains are possible by deadheading or by connecting different lines to reduce layover time. Nevertheless, this conventional estimation method is not suited for rail DRT. The rail DRT system is not necessarily symmetric. In fact, whenever there is a difference in demand between two opposite directions, there will automatically be an asymmetric service frequency. Moreover, the rail DRT system offers ample possibilities for optimizing vehicle circulation. Simple vehicle round trips are unlikely. Altogether it must be concluded that traditional methods for determining fleet size are not applicable.

One could develop an envelope for the fleet size approximation. The most conservative indication assumes full round trips for vehicles on all OD-pairs. The factor of 1.32 in equation 3-18 will be 2.0 in that case. In the most optimistic case, all vehicles can be deployed on a new route directly upon arrival at their destination. In that case, the factor of 1.32 in equation 3-18 decreases to 1.0. Note that the upper bound of 2.0 could theoretically be higher, because deadheading vehicles have not been included in node and arc capacity utilization equations. Consequently, the vehicles which are returning to their station of origin cause additional delay at nodes and links which they occupy during deadheading. Thus, the travel time approximation would be too optimistic.

Ultimately, the fleet range between the most conservative and most optimistic case is too large to create an envelope of interest. Therefore, the fleet size approximation of equation 3-18 is used as sole indication.

3.5.7 The issue of varying travel demand and invariable infrastructure

A major challenge is that infrastructure requirements at one moment in time could be different from another moment when travel demand is dissimilar. When trading-off infrastructure capacity to operational costs and passenger costs, it would be unrealistic to have a different infrastructure available at one time moment compared to the next. The solution is to store the maximum infrastructure capacity over all time frames. This will be the infrastructure capacity which must available at any time. Figure 3.3 shows the methodology.

One particular input in step 1 of figure 3.3 is an initial infrastructure capacity. In an existing network, this input is trivial. However, in a numerical experiment with a fictional network, an initial capacity must be designed. The approach is as follows. All demand is forced to take the shortest route based on uncongested travel time. The infrastructure is then set such that capacity utilization is 65% on the entire network, in line with the UIC advice from section 3.5.1.

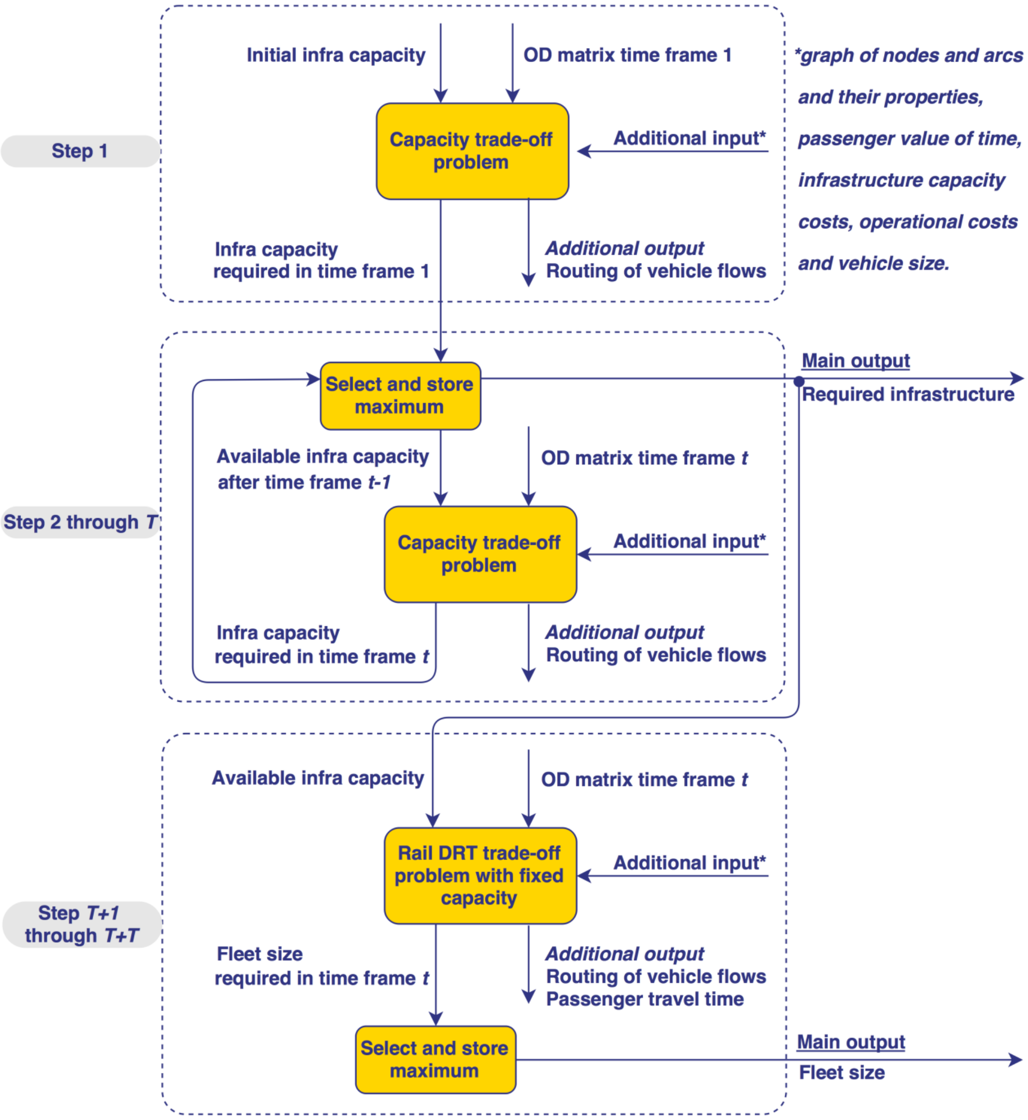


Figure 3.3: Solution to varying travel demand and invariable infrastructure.

Alternatively, one could aim for levelling the flow through each node as a basis for setting an initial infrastructure capacity. This is achieved by routing the flow such that smallest variance in node betweenness centrality is attained. The benefits of applying this method (for example a quasi-equal node capacity) is judged not to outweigh the additional complexity. The method will not be used.

Once the required infrastructure capacity has been selected, a revision of all time steps is needed. With the infrastructure capacity now being fixed (limited decision variables), optimal routing of flows could be different. Travel time benefits or operational cost reduction may be possible. The largest fleet size over all time frames represents the required fleet size.

3.6 Rail DRT model overview

The structure and basis of the rail DRT model has been presented in section 3.4.4. The individual elements of the model have been discussed in detail in section 3.5. A concise overview of the final rail DRT model is provided hereafter in table 3.3.

Rail DRT model

Table 3.3a: Decision variables.

D1	Flow on arc a originating at o having destination d	$x_a^{(o,d)}$
D2	Capacity of arc a	c_a
D3	Capacity of node j	s_j

Table 3.3b: Available parameters and sets.

S1	Set of all nodes in the network	$N = [1,2,\dots,n]$
S2	Set of available arcs in the network	$A = [(i,j)_1,(i,j)_2,\dots,(i,j)_l]$
S3	Arc length	$A_L = [L_1,L_2,\dots,L_l]$
S3	Arc free speed	$A_v = \left[V_{1_{free}},V_{2_{free}},\dots,V_{l_{free}}\right]$
P1a	Scaling parameter of the logistic speed-density function	α
P1b	Shifting parameter of the logistic speed-density function	β
P2	Hourly OD-matrix	P
P3	Hourly costs of track infrastructure capacity	E_1
P4	Hourly costs of station platform capacity	E_2
P5	Operational costs per seat kilometre	E_3
P6	Passenger value of time	E_4
P7	Dwell time	t_d
P8	Vehicle seating capacity	z
P9	Average vehicle load factor	ξ
P10	Platform length	L_p
P11	Maximum number of vehicles per hour per unit of arc capacity	y

Table 3.3c: Derived parameters and sets.

S12	Set of OD-pairs	$OD = [(o,d)_1,(o,d)_2,\dots,(o,d)_b]$

Table 3.3d: Objective function definition.

OF	$\min\left[E_1\cdot\sum_{A} c_a\cdot L_a + E_2\cdot L_p\cdot\sum_{N} s_j + E_3\cdot z\cdot\sum_{OD}\left(\sum_{A} x_a^{(o,d)}\cdot L_a\right) + E_4\cdot\sum_{OD} T_{veh}^{(o,d)}\right]$

Table 3.3e: Constraints.

C2	Travel time function (3-1 through 3-14)	$T_{veh}^{(o,d)} = f\left(x_a^{(o,d)}, c_a, s_j, L_a, V_{a_{free}}, P(o,d), t_d, \xi, z, y\right),$	$\forall\ (o,d) \in OD$
C3	Flow cannot be negative	$x_a^{(o,d)} \geq 0\ ,$	$\forall\ a \in A$ $\forall\ (o,d) \in OD$
C4.1	Flow continuity at all intermediate nodes k	$\sum_i x_{(i,j)}^{(o,d)} = \sum_j x_{(j,k)}^{(o,d)}\ ,$	$\forall\ (o,d) \in OD$ $\forall\ j \in N$ $j \neq d\ \&\ j \neq o$
C4.2	Demand satisfaction at origin	$\sum_k x_{(o,k)}^{(o,d)} = P(o,d)\ ,$	$\forall\ (o,d) \in OD$
C4.3	Demand satisfaction at destination	$\sum_i x_{(i,d)}^{(o,d)} = P(o,d)\ ,$	$\forall\ (o,d) \in OD$
C5	Link capacity cannot be negative	$c_a \geq 0\ ,$	$\forall\ a \in A$
C6	Node capacity must be a positive integer	$s_j \in \mathbb{Z}^+\ ,$	$\forall\ j \in N$
C7	Density cannot exceed 1.0	$\rho_j \leq 1.0\ ,$	$\forall\ j \in N$

For verification purposes, the following unit consistency check is performed. Consider the objective function in table 3.3d. It has four elements: arc and node capacity costs, operational costs and travel time costs. The units of each are listed below. It is concluded that the objective function is consistent.

	c_a:	$[-]$
	L_a:	$[km]$
	E_1:	$[€/(km \cdot hr)]$
Arc capacity costs:	$E_1 \cdot \sum_A c_a \cdot L_a$:	$[€/hr]$
	s_j:	$[platforms]$
	L_p:	$[m/platform]$
	E_2:	$[€/(m \cdot hr)]$
Node capacity costs:	$E_2 \cdot \sum_N s_j \cdot L_p$:	$[€/hr]$
	$x_a^{(o,d)}$	$[vehicles/hr]$
	z	$[seats/vehicle]$
	E_3:	$[€/seatkm]$
Operational costs:	$E_3 \cdot \sum_{OD} x_a^{(o,d)} \cdot L_a \cdot z$:	$[€/hr]$
	$T_{veh}^{(o,d)}$	$[passengerhours/hr]$
	E_4:	$[€/passengerhour]$
Travel time costs:	$E_4 \cdot \sum_{OD} T_{veh}^{(o,d)}$	$[€/hr]$

4. Model implementation

The mathematical formulation of the rail DRT model has been defined and presented in chapter 3. The next chapter discusses the model implementation into Matlab. First, section 4.1 justifies the choice of Matlab as optimization tool over other alternatives. Section 4.2 holds a detailed description of necessary adaptions made to the model during implementation and shows the applied Matlab file structure. The files are available at request. Finally, section 4.3 concerns verification and validation.

4.1 Optimization tool

Two optimization tools have been considered for implementing the rail DRT model: CPLEX and Matlab. Ultimately, Matlab has been selected as preferred option. The following paragraphs describe the trade-off and reflect on Matlab's abilities, capabilities and restrictions.

Van Nes (2002) illustrates the main challenge in finding an optimization tool which can solve public transport network design problems: "It can easily be seen that the number of possible solutions increases more than exponentially with the size of the problem, which makes it a hard problem to solve. It has been shown that the network design problem in its simplest form is NP-complete, that is, no algorithm exists that can solve the network design problem in acceptable computation time."

First intention was to use CPLEX for solving the rail DRT problem. Considerations for preferring CPLEX include its known adequate performance when solving optimization problems with a vast amount of decision variables; its compatibility with data processing tools for enabling swift handling of results; and prior experience of the author using CPLEX for airline operation problems. Unfortunately, while being very powerful in solving linear problems, CPLEX is not well suited for non-linear problems. The travel time function in constraint C2 of the rail DRT problem is non-linear and cannot be approximated by a linear relation without making unreasonable assumptions or creating very limiting restrictions.

As an alternative to CPLEX, the built-in optimization toolbox in Matlab is used. While the toolbox is somewhat less convenient to use in comparison to CPLEX, it is very powerful and can handle non-linear problems. The governing principle behind Matlab's optimization toolbox for constrained non-linear problems is a trust-region method. It is assumed that the reader is familiar with the basics of such methods. Else, the reader is kindly referred to relevant literature on the subject such as by Byrd, Schnabel and Schultz (1987).

Trust-region methods involve computation of a full eigensystem. The duration thereof is proportional to several factorizations of the Hessian matrix at the location under consideration. For time constraints in large scale problems such as the rail DRT model, Matlab turns to heuristic approaches. The basic principle is to solve a sequence of approximate minimization problems defined from the original problem. A full discussion of Matlab's functionality would be beyond the scope of this thesis. However, there is one aspect which must be discussed: the ability to find a global optimum.

Finding the global optimum is a point of concern, in particular when the global optimum is outside the initial solution's basin of attraction. Matlab attempts to cover this issue by separating the optimization problem into a two-step approach. First, trying to force the solution towards a global optimum in the first step and only later focus on finding fast local convergence. Nevertheless, without linearization of the optimization problem, there is no full guarantee that Matlab indeed finds the global optimum. This remains a point of concern and is addressed again later in the verification and validation section.

4.2 Changes in model formulation

Figure 4.2 and appendix H show the Matlab file structure and variable definition. In general, all equations and variables have been implemented into Matlab in accordance to the mathematical formulation of the rail DRT model from chapter 3. In some cases, the very nature and functionality of Matlab called for a different approach. These deviations in model formulation are discussed next.

4.2.1 Factorial replaced by approximation

The calculation of factorials can be a lengthy aspect in any model implementation. Analysis showed that computation of factorial values in the queuing theory function took approximately 30% of all running time. A first, non-adopted, solution was to create a list of factorials. During every iteration, the required factorial was retrieved from the list rather than created repeatedly. However, running time improvement was not satisfactory. Moreover, a second challenge arose. In non-linear problems, the Matlab optimization tool cannot restrict its decision variables to integer numbers. This is possible in linear problems only. An option is to round the variables to integers after every iteration. If correct, the decision variable should automatically tend towards integers then. Unfortunately, due to truncation effects, there were errors in computing or retrieving the factorials. Therefore, the factorial has been replaced by Ramanujan's expression, a continuous function which approximates the factorial. Consequently, all decision variables are continuous now.

4.2.2 Matlab's inability to satisfy constraints: magnifier multiplications

Although Matlab is powerful in handling large scale problems, constraints are not always fully respected. For example, flow density at nodes should not exceed unity. Else, there would be negative waiting times. However, Matlab does allow the constraints to be violated slightly, because it only watches the cumulative violation. Consequences are substantial. For example, constraint C7 imposes that $\rho_j \leq 1.0$, but if Matlab allows a node to have a density of $1.0 + 10^{-9}$, the waiting time at that particular node is close to minus infinity. As a result of this small constraint violation, the objective function shows negative monetary values, which is obviously incorrect. A workaround which has been applied, is to multiply the values in every constraint by a large number, for example one million. Then, small violations in decision variables are exaggerated. Unfortunately, the choice of multiplier value has an effect on Matlab's ability to find a solution at all. The underlying cause is associated with the high complexity of several built-in Matlab functions. By trial-and-error, the most appropriate multiplication factors have been selected.

4.2.3 Fixed route choice sets

Model running time tests were disappointing at first. Solving the rail DRT problem on a network with just 7 nodes, 18 arcs and 20 OD-pairs took 30 minutes. The large number of decision variables was identified as the main cause. Every arc is a separate decision variable for every single OD-pair and all nodes need balancing for every OD-pair. The fictional test network is shown in figure 4.1. The number of decision variables associated with this network is 385, which is composed as follows: 7 node capacities, 18 arc capacities and $18 \cdot 20 = 360$ vehicle flows.

To reduce the number of decision variables in the model and to cut running time, the following methodology has been implemented. The model uses a fixed set of route choices per OD-pair instead of arc-based vehicle flow assignment. New decision variables are the share of vehicle flow routed via each route option. Note that r routes for an OD-pair correspond to $r - 1$ decision variables, because the share on the last route is set implicitly. Table 4.1 shows the decision variables in the original and redefinition of the problem. In the fictional test network, the number of decision variables reduces to 52, which is composed of 7 node capacities, 18 arc capacities and 27 routing shares. The latter corresponds to 11 OD-pairs which have 2 routing options (so there is one decision variable associated with it), 2 OD-pairs which have 3 routing options (so two decision variables) and 4 OD-pairs which have 4 routing options (so three decision variables); combined: $11 \cdot 1 + 2 \cdot 2 + 4 \cdot 3 = 27$.

Table 4.1: Redefinition of decision variables in the rail DRT problem to include fixed route choice sets.

Original problem	Redefinition
• Flow per arc per OD-pair • Arc capacity • Node capacity	• Share of vehicle flow routed via each route option per OD-pair • Arc capacity • Node capacity

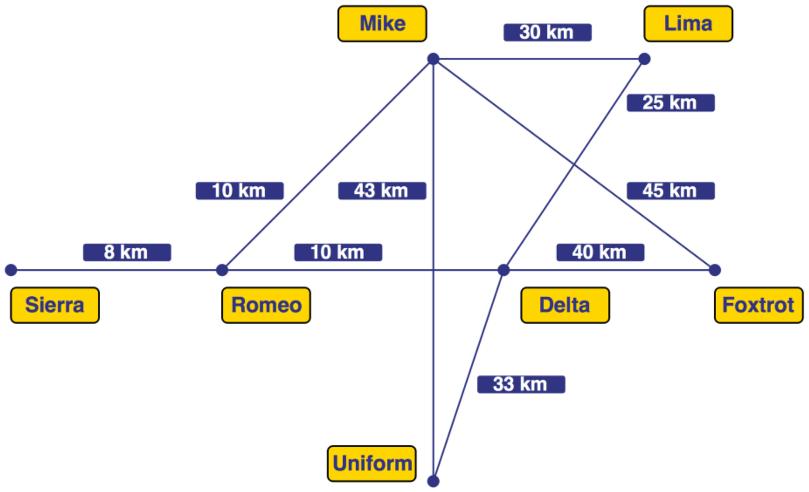
Consequently, the rail DRT optimization problem is preceded by a process of determining all possible routes in the network between each OD-pair. Loops are not included. Neither are routes which are longer than the shortest route multiplied by a certain factor of choice. For example, no routes are included which exceed the shortest route length twice or thrice, based on free flow travel time.

Note that in the new definition, many constraints are no longer needed. This includes all constraints which ensure flow continuity. On the other hand, a constraint must be added such that the share of flow per route must be between 0 and 1. Also, in case of more than two routes, the cumulative share of flow on route options 1 through $n-1$ must be between 0 and 1. The objective function and functionality of the model remain the same.

In the fictional network of 7 nodes, 18 arcs and 20 OD-pairs, the number of decision variables is reduced from 385 to 52 (approximately a factor 7). In a larger fictional network of 28 nodes, 57 arcs and 585 OD-pairs, the number of decision variables is reduced from 33430 to 1600 (reduction factor of 20). In general, the number of decision variables is reduced by a factor equal to the ratio of average number of arcs per OD-pair to the average number of route options per OD-pair.

Running time for the fictional network of 7 nodes, 18 arcs and 20 OD-pairs went down from 30 minutes to 15 seconds, including pre-processing of the data to find all available routes. The larger network, which could not be solved in reasonable time in the original model definition, now takes approximately 30 seconds.

Running time remains quite lengthy when there are many route options per OD-pair, for example in case of highly symmetric networks. Such running time was not anticipated. Therefore, a different approach for setting up the initial solution has been implemented. Previously, all demand was assigned to the shortest route and it was left to the optimization tool to send some demand via longer route alternatives. In the final implementation, the demand is initially distributed according to a weight factor which is inversely proportional to the cube of the free flow travel time per route option. This approach for setting up an initial solution decreased running time by approximately 5%.



Origin	Destination	Demand [pax/hr]
Sierra	Mike	700
Sierra	Uniform	490
Sierra	Lima	350
Sierra	Foxtrot	210
Mike	Sierra	840
Mike	Uniform	630
Mike	Lima	70
Mike	Foxtrot	280
Uniform	Sierra	420
Uniform	Mike	560
Uniform	Lima	140
Uniform	Foxtrot	350
Lima	Sierra	490
Lima	Mike	630
Lima	Uniform	70
Lima	Foxtrot	70
Foxtrot	Sierra	560
Foxtrot	Mike	210
Foxtrot	Uniform	280
Foxtrot	Lima	70

Figure 4.1: Fictional network used for running time tests. Free speed on all arcs is 100 km/hr.

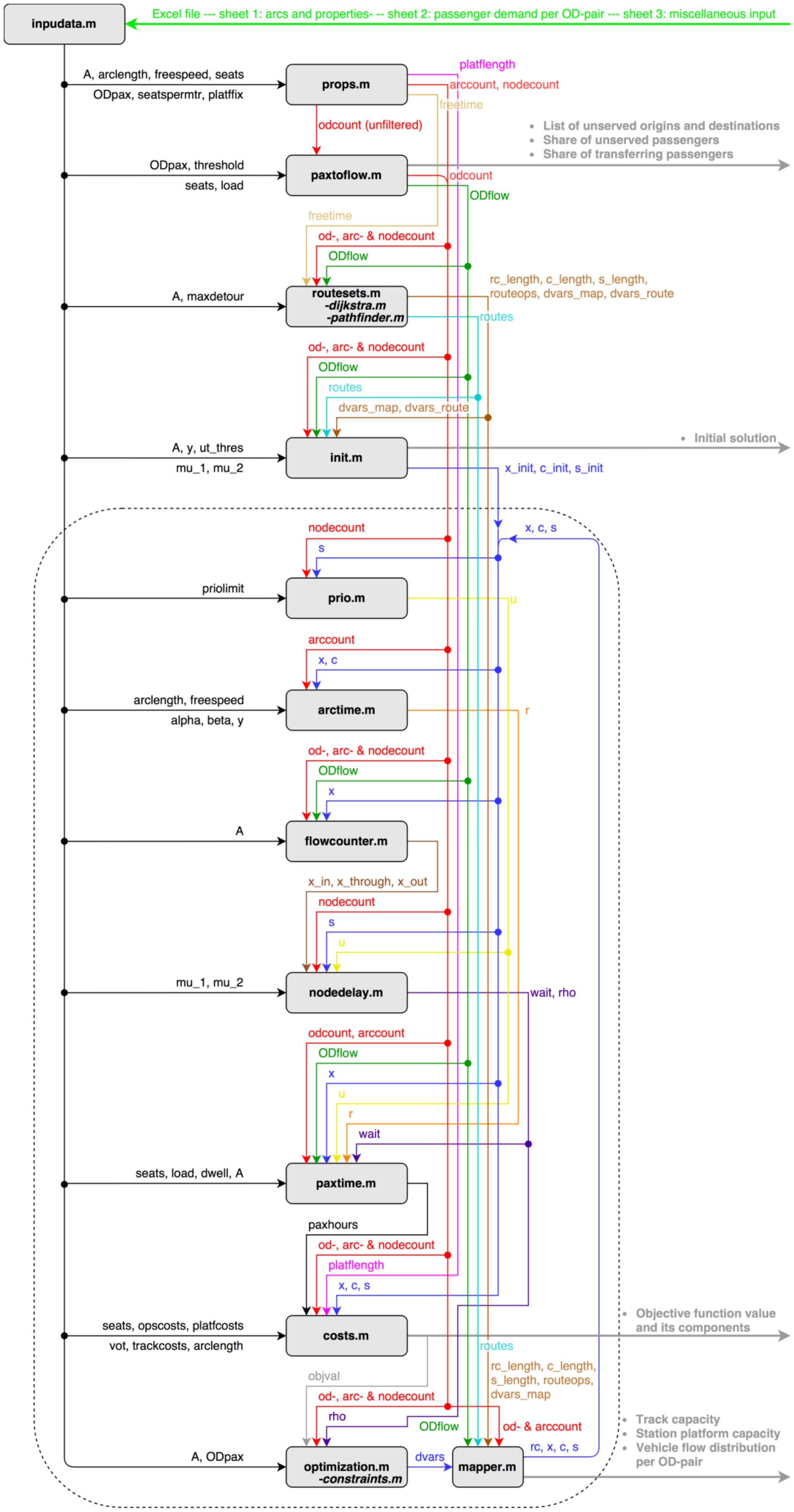


Figure 4.2: Matlab file structure, variable names and interrelation; appendix H holds an explanation per file and variable.

4.3 Verification and validation

The traditional transhipment problems (table 2.1 and 3.1) have been solved in Matlab for a fictional network of seven nodes out of which five have demand, supply or both. The network as such has 90 decision variables in the x_a^d formulation (distinction by destination only) or 360 decision variables in the x_a^{od} formulation (distinction by OD-pair). Results in the x_a^d case have been verified against the solution provided by Excel's solver tool. The x_a^{od} case could not be verified in Excel because Excel has a limit of 200 decision variables.

The final Matlab model has been verified in segments and as an integral system. First, concerning the separate segments, each element of the model has its own built-in verification tool, which can either stop the model altogether or merely produce a warning. For example, in the conversion process from passenger demand to vehicle flow, there is a sanity check that no station is left unserved and that all stations are defined in alphabetical order, which is a prerequisite by Matlab. If the first principle is violated, Matlab will output a warning, in the second case, the model will quit to prevent errors.

To test the model as an integral system, a variety of input scenarios has been run for verification. The first is to set passenger value of time to zero. In that case, the component of travel time costs should disappear from the objective function. Consequently, the model has to balance the remaining components of infrastructure capacity costs and operational costs. Given that the latter is defined per seat kilometre, all vehicles should take the shortest route and infrastructure can be minimized, because travel time is irrelevant. This is exactly what the model showed to do.

Another scenario is a network with only one OD-pair connected via two equal-length branches. Given the exponential delay-density function, the optimal solution is an equal distribution of demand over both branches. Again, this was performed correctly by the model.

Finally, the issue of global and local optima is raised again. In the old definition of the rail DRT problem, that is prior to using a fixed route set per OD-pair, Matlab sometimes found an 'optimal' solution which had a larger objective function value than the initial solution. This issue occurred significantly less frequent after implementing the fixed route set approach.

To assess the validity of results provided by Matlab's optimization toolbox, it has been studied if different initial solutions result in different objective function minima. Twenty random initial solutions have been generated. To be more specific, the share of flow per route option has been selected randomly and the arc- and node capacity have been specified like before (attain 65% capacity utilization). In 16 out of 20 runs, the solution was exactly the same, both in objective function value and decision variable setting. In the remaining 4 runs, the solution was vastly different, with the objective function value being a factor 100 to 1,000,000 higher than the common value found in the aforementioned 16 cases. This makes it justifiable, although not scientifically proven, that the solution found in the 16 runs can be used for drawing relevant conclusions. During generation of results in chapter 5 and 6, two methods of results generation are applied: using the original definition (all flow via the shortest route option) and using the new definition (according to a weight factor which is inversely proportional to the cube of the free flow travel time per route option). Only in case the results from both initial solutions were equal, have the results been used. This appeared to be the case in all scenarios studied.

Naturally, given that no rail DRT system is in operation yet, the model cannot be validated against empirical data. This emphasises the importance of the sensitivity analysis into a variety of input variables. Chapter 5 is devoted to this topic.

The model implementation has been tested to meet the requirements set in section 3.4.4.

5. Numerical experiments and model exploration

The main research question calls for studying the relations between a variety of network properties and operational performance indicators in a rail DRT system. Chapter 1 proposed to run various fictional scenarios to analyse the aforementioned relations. Furthermore, it has been suggested during model development and model implementation to apply a sensitivity analysis on some of the input variables. Both aspects are combined into a set of numerical experiments. These are topic of the following chapter. First, section 5.1 describes the fictional networks which are used. Next, section 5.2 develops the base case scenario and section 5.3 discusses the results. Section 5.4 and 5.5 define the input scenarios in the numerical experiments and present corresponding results.

5.1 Applied network structure

The numerical experiments are performed using a network composed of 17 nodes and 48 single-direction arcs. Two distinct graph structures are considered. The first is a grid, while the second is a ring/radial structure. Figure 5.1 shows these two network types. The upcoming paragraphs describe the development and rationale behind this specific grid and ring/radial structure. Starting point in that process is the classification of typical network structures in public transport by Van Nes (2002). Further selection is based upon comparison with existing railway networks around the globe.

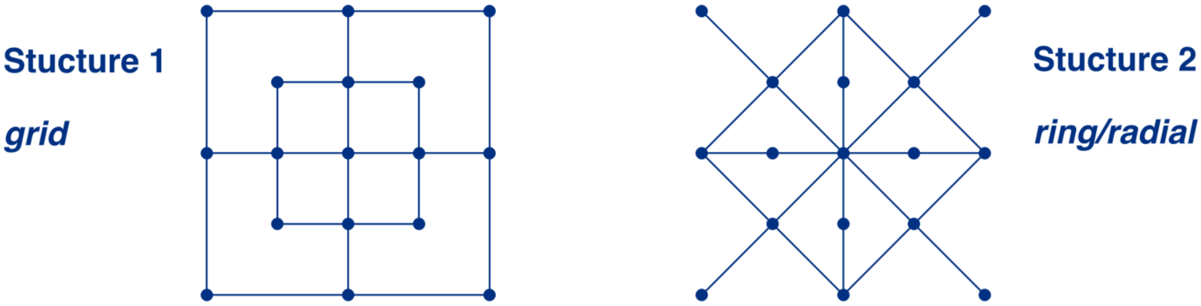


Figure 5.1: The two graph structures considered in the numerical experiments. All lines represent bidirectional arcs.

5.1.1 Selecting the preferred network structure based on typical structures in existing rail networks

Van Nes (2002) identifies seven typical network structures in public transport systems, shown in figure 5.2. The ideas by Van Nes hold for public transport in general, including both rail and road bound systems. This thesis focusses specifically on rail, so the set of typical network structures is assessed for familiarity with rail applications. Only the most relevant options are selected for further use.

The railway network in The Netherlands as a whole does not show clear commonality with any of the network structures in figure 5.2. Nevertheless, some sections of the Dutch network can be categorized into one of the typical structures, although the resemblance is limited. Examples include a radial network out of Utrecht Centraal and Zwolle, a ring/radial structure of the greater Randstad area and various linear elements on outer branches of the network. Figure 5.5 shows the radial and ring/radial structures in the Dutch railway system.

Expanding the scope to a global level, there is a variety of railway networks which do fit the typical structures. Some examples are the French ring/radial system extending out from Paris, the Chinese main line grid and the Chinese ring/radial network around the city of Hefei. Figure 5.6 presents these foreign rail networks. Considering that ring/radial and grid structures are frequently recurring network types, it is justifiable to limit Van Nes' original set of structures to just the aforementioned two.

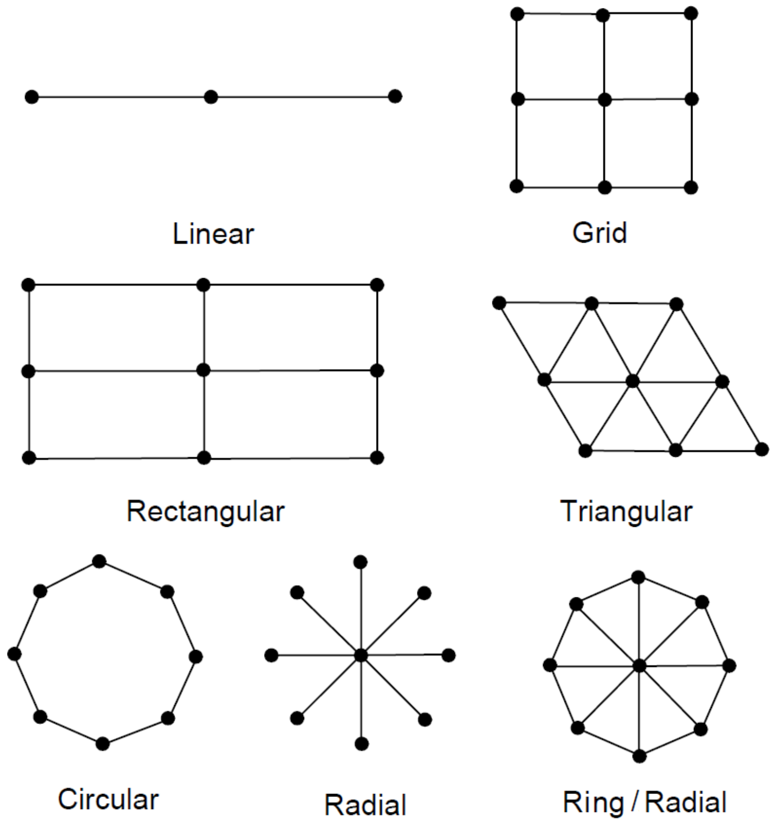


Figure 5.2: Typical network structures in public transport systems (Van Nes, 2002).

5.1.2 *Sizing and constructing the preferred networks*

The choice of network structure has implications for the preferred network size. A fair assessment of results requires the different network structures to be equal in size and demand. In other words, there shall be one set of nodes and corresponding demand between them, while the network must be constructed from a fixed set of arcs. It is a challenge to construct two entirely different network structures with these constraints.

Note that a ring/radial structure requires one central node from which the radial arcs extend outwards. Moreover, the ring/radial network preferably is symmetric. The smallest option which fits the requirements is a network consisting of nine nodes: one central node with eight surrounding nodes. Figure 5.3 shows the corresponding grid structure and ring/radial structure. Both network types do not differ except for a small set of diagonal nodes. Furthermore, the number of arcs in the grid structure is lower than in the ring/radial alternative. This violates the principle of equal number of nodes and arcs.

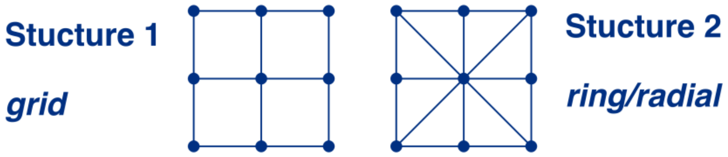


Figure 5.3: Grid and ring/radial structure in a nine-node network.

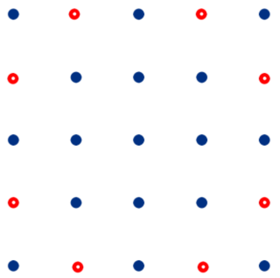


Figure 5.4: In a 25-node network the marked nodes can be removed without consequences for building a grid or ring/radial structure.

A network of 25 nodes would be the next option to consider. With growing network size comes an increase of model computation time. Preferably, the number of nodes is restricted. Figure 5.4 illustrates that eight nodes can be removed from the network without limiting its possibilities to be characterized as a ring/radial structure. If the network with the remaining nodes is constructed like a grid, it does not have equal grid size. Nevertheless, there is no constraint which requires all grids to be equal in size. It takes 24 bidirectional arcs to construct the grid. Radials from the centre node add up to 16 bidirectional arcs. Another 8 are used to form a ring around the centre, making a total of 24 again. The ring is chosen such that it connects different nodes compared to the grid network. Ultimately, the resulting networks are shown in figure 5.1.

Figure 5.5a: Radial networks around Utrecht and Zwolle.

Figure 5.5b: Ring/radial network in the greater Randstad.

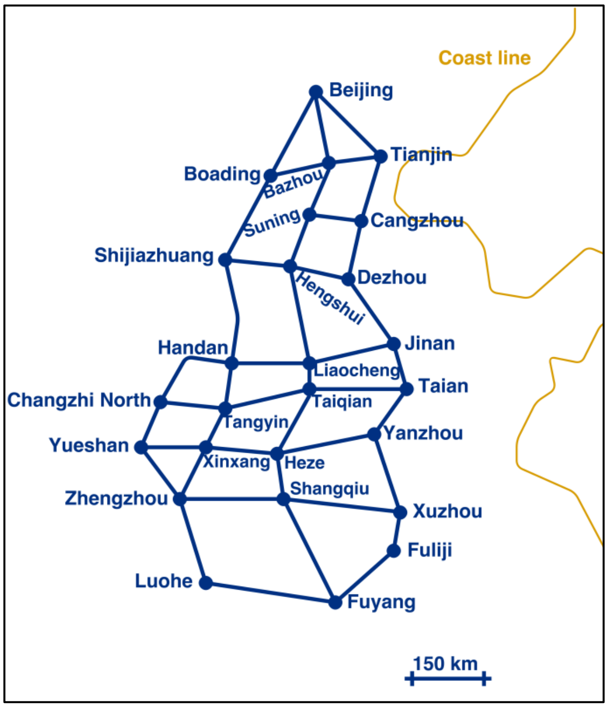


Figure 5.6a: Grid network of main railway lines in China.

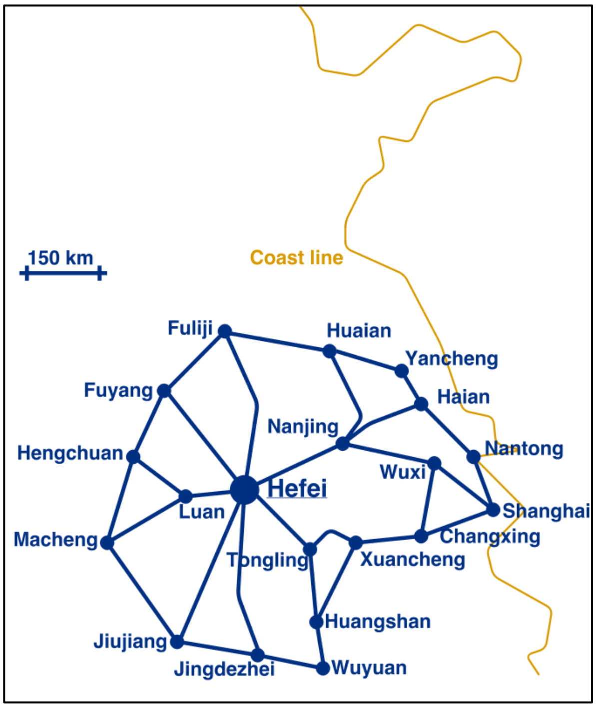


Figure 5.6b: Ring/radial rail network around Hefei in China.

5.2 Base case scenario description

Starting point of the numerical experiments is a base case scenario. Table 5.1 lists all input variables of the rail DRT model and their corresponding values in the base case scenario. Passenger demand distribution in the base case is presented in appendix E. The following sections describe and justify the choices leading to the base case scenario.

Table 5.1: Input variable values in the base case scenario (please refer to appendix E for passenger demand distribution).

Variable	**Description**	**Value**
C	Maximum continuous capacity utilization according to UIC advice [-]	0.65
$E_{1_{30\ year}}$	Track capacity costs [*millions of euros per 30 year per kilometre of single track*]	50
$E_{2_{30\ year}}$	Platform costs [*millions of euros per 30 year per 200 metre of platform*]	650
E_3	Operational costs [*euros per seat kilometre*]	0.02
E_4	Value of time [*euros per hour*]	10
fr_{max}	Maximum allowed detour factor for selecting route options [-]	1.5
Lp_{fix}	Platform length, fixed component [*meter*]	30
Lp_{var}	Platform length, vehicle dependent component [*seats per meter*]	3
s_{prio}	Number of platforms required to have a priority system in queuing theory [-]	3
t_d	Dwell time [*seconds*]	20
v_{min}	Minimum service frequency in order to have a service [-]	3.00
y	Track capacity [*vehicles per hour*]	180
z	Vehicle capacity [*seats*]	24
α	Scaling parameter of the arc speed-density function [-]	-11.17
β	Shifting parameter of the arc speed-density function [-]	0.88
ξ	Load factor [-]	0.70
$1/\mu_1$	Mean service time non-stop vehicles [*seconds*]	5.0
$1/\mu_2$	Mean service time dwelling vehicles [*seconds*]	80

5.2.1 Demand

Recall from section 5.1 that a fair assessment of results requires the different network structures to have equal demand. Therefore, a demand distribution is developed based upon the location of nodes in the network, independently from the available arcs. Appendix E presents this demand distribution. The underlying principle is a gravity model using Euclidean distance between the nodes. Any other approach, such as correcting for node centrality, would have violated the principle of independency from network connectivity.

The fictional networks of 17 nodes have $16 \cdot 17 = 272$ unique OD-pairs. In case of a uniform distribution with 125 passengers per hour on each OD-pair, the total hourly demand is 34,000. By engineering assumption, this number is taken as a reference. It is distributed over the OD-pairs based on relative share of demand computed by a gravity model. Input to the gravity model is the Euclidean distance between origin and destination, assuming a unit grid length for the node locations in figure 5.7. Equations 5-1 through 5-4 describe the process of determining demand per OD-pair.

$$d_{(o,d)}^2 = (x_d - x_o)^2 + (y_d - y_o)^2 \tag{5-1}$$

$$w_{(o,d)} = \frac{1}{d_{(o,d)}^2} \tag{5-2}$$

$$w_{total} = \sum_{(o,d)\in OD} w_{(o,d)} \qquad 5\text{-}3$$

$$P(o,d) = \frac{w_{(o,d)}}{w_{total}} \cdot P_{total} \qquad 5\text{-}4$$

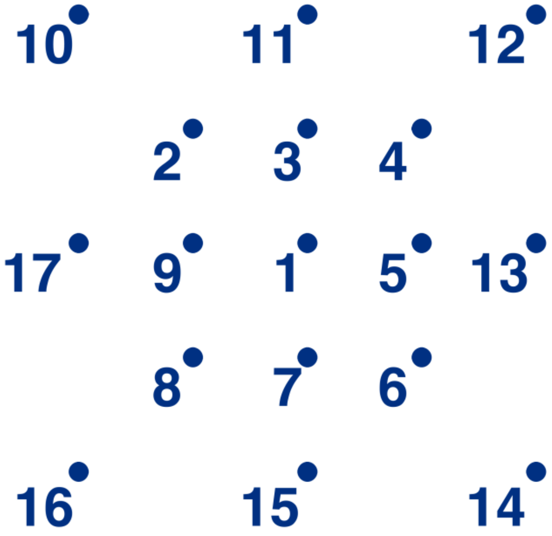


Figure 5.7: Node numbers in the fictional networks.

5.2.2 Network characteristics

Figure 5.1 is to scale. There are arcs of unit length, twice unit length and $\sqrt{2}$ times unit length. Each unit is set to represent 6 kilometres, based on comparison with the existing railway network in The Netherlands. While the fictional networks in the numerical experiments do not represent any existing railways directly, some base case parameters are defined by comparison with existing networks. This principle has been used before when selecting the most relevant network structure and is applied again to set the unit arc length. In the Netherlands, average interstation distance is approximately 6.12 kilometres. Appendix G presents the corresponding data. By assumption, every arc has a free speed equal to $V_{a_{free}} = 100$ kilometres per hour.

5.2.3 Arc speed-density relation

The parameters α and β scale and shift the logistic speed-density function defined in equations 3-1 and 3-2. The reader is kindly referred back to section 3.5.1 for an explanation of this function, which governs the speed of rail vehicles per arc in relation to the arc's infrastructure utilization. The base case scenario values of α and β are defined from a UIC advise on maximum capacity utilization in rail and the relative abrupt nature of the logistic speed-density relation in autonomous systems. The UIC suggests that capacity utilization should be lower than approximately 60 to 70% on a daily basis to ensure robust operations. During peak hours, the upper bound is 75 to 80%. By engineering assumption these values are transformed into the speed reduction factors shown hereafter. Figure 5.8 shows the corresponding logistic speed-density relation.

$$f_v(\varphi = 0.8) = 0.7, f_v(\varphi = 1.0) = 0.2$$

Solving for parameters α and β yields:

$$\alpha = -11.17, \beta = 0.876$$

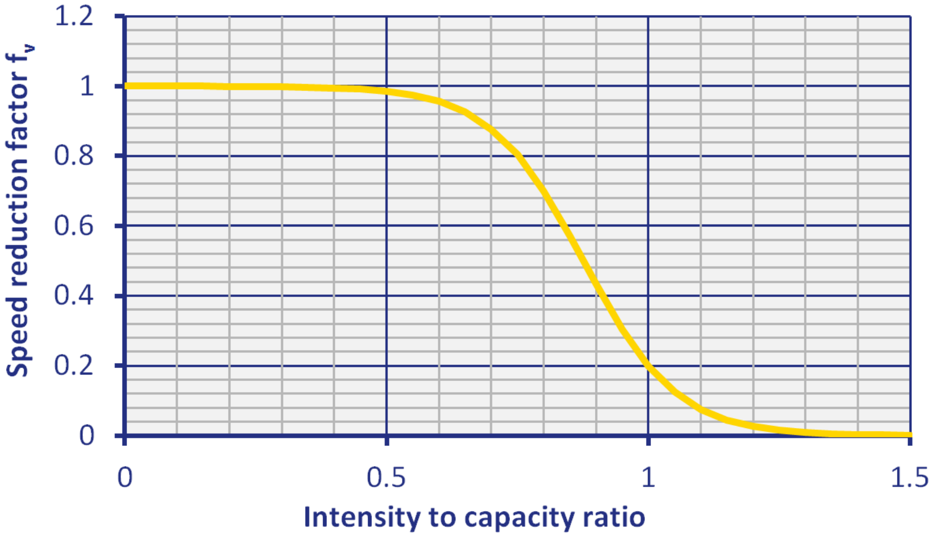


Figure 5.8: Arc speed-density relation in the base case scenario.

Naturally, the parameter values may be considered arbitrary. Validation is impossible because there are no rail DRT systems in operation. A suggestion is to validate the logistic speed-density relation against train logging data in the current NS network. Regularly, an occasional train is added to the schedule, increasing the φ-ratio, for example in case of rolling stock ferrying to maintenance depots. These additional trains are a potential source of delay. Relating the severity of experienced delays to the change in φ-ratio, is an approach to validating parameters α and β.However, the nature and characteristics of the current supply driven system are vastly different than in a rail DRT system.

Furthermore, there are hardly any cases in which more than one occasional train is added to the schedule, limiting the validation scope. Altogether, the applicability and reliability of this validation method is considered inadequate. Therefore, rather than validating the chosen parameter values to empirical data, there will be a sensitivity analysis into the effects of selecting different α and β. The range of values and scenarios are discussed in section 5.4.

5.2.4 Node delay-density relation

Waiting time at nodes is based on queueing theory. Fundamental input to the corresponding equations is service time. For dwelling vehicles, it is judged a reasonable assumption to define service time as four times the dwell time. The underlying principle is that servicing includes the following four processes: setting switches, pulling into the station, dwelling and clearing the platform. These events are considered approximately equal in duration.

Current sprinter trains are scheduled to dwell for 24 seconds. Based on visual inspection of boarding time at the Rivium Parkshuttle, it is assumed that dwell time can be reduced to $t_d = 20$ seconds in rail DRT. Correspondingly, the mean service time of class 2 vehicles is $1/\mu_2 = 80$ seconds. Please refer to appendix C for an elaborate description of the Parkshuttle boarding time observation.

The mean service time for non-stop vehicles is more difficult to estimate. The precursory explanation of equal length service time components yields a 20 second duration of setting switches. However, if two consecutive vehicles are routed via the same tracks, there is no need to set switches differently. In that case, the 'service' time is as short as the minimum allowed time headway between two vehicles. This reduction in service time is particularly prominent at stations which have limited routing options. Overall, by reasonable judgement, the mean service time of class 1 vehicles is set to $1/\mu_1 = 5.0$ seconds.

5.2.5 Minimum service frequency, vehicle capacity and average load factor

The conversion from passenger demand to service frequency is performed per OD-pair separately and has been described in section 3.5.3. The conversion process depends on three variables: v_{min}, z and ξ. The 2015 study by Haverkamp & Maat provides an indication of the average load factor and preferred vehicle size in rail DRT as a substitute of scheduled heavy rail: load factor $\xi = 70\%$ and vehicle capacity $z = 24$ seats. It is expected that the choice of vehicle size may have a profound impact on the model's output, in particular because it is related directly to service frequency $v_{(o,d)}$ and consequently to capacity utilization. It is suggested to study the effects of varying z in a sensitivity analysis. There is no need to vary ξ, because it has the same inversely proportional relation to $v_{(o,d)}$ as z has. By contrast, the range over which ξ can be varied is limited, while the range of z is (infinitely) broader. Therefore, it is preferred to include only z in a sensitivity analysis.

Selecting a base case value for v_{min} is a trade-off between operational and scientific preference. The higher the value of v_{min}, the bigger the share of unsatisfied demand, since less OD-pairs are served directly. From the operator's point of view, v_{min} could have a high value though, because a larger v_{min} results in a higher service frequency on the OD-pairs which are served (at the cost of less OD-pairs which are served directly). This is particularly beneficial when benchmarking rail DRT to the current system at a v_{min} which is higher than current train frequencies. On the other hand, from a scientific viewpoint there is no profound argument to have a high value for v_{min}. After all, the DRT system aims at operating in accordance to demand. Narrowing the range of available service frequencies by selecting a high v_{min} counteracts the very principle of DRT. Therefore, v_{min} would preferably be set to 1.0. In other words, an OD-pair with sufficient demand for at least one departure per hour will have a direct service. However, running time constraints impose to use 3.0 instead.

5.2.6 Passenger costs

Passenger costs are directly proportional to travel time. The average train passenger's value of time is €10,-. Extensive research has been conducted over the years into value of time. It is assumed to be a well-known reference number, commonly used by NS and other stakeholders alike. Value of time is sufficiently accurate to omit a sensitivity analysis. A point of attention is the variation of value of time among different travel purposes. For example, business travel has almost thrice the value of leisure.

5.2.7 Infrastructure costs

Two elements are involved in determining infrastructure costs. The first is the theoretical capacity of a single direction track. The second includes all parameters which describe platform length, platform capacity costs and track capacity costs.

First, consider the theoretical capacity of a single direction track. Its value is based on references from autonomous driving and high frequency railway systems. In traditional traffic theory, a capacity of 2200 vehicles per hour per lane is a commonly applied rule of thumb. Tientrakool et. al. (2011) estimated that highway capacity increases by a factor 1.8 in case of 50% penetration rate of level-4 automated vehicles. The new capacity would be 4000 vehicles per hour per lane. By intuition, such numbers do not appear representative for a rail system, even in a system of autonomous vehicles in a homogeneous fleet. In a conventional train system with traditional block system signalling, the theoretical capacity of one single direction track is approximately 20 to 30 trains per hour in heavy rail or up to 40 trains per hour in light rail and metro systems. Recall from the literature study that current people mover systems are able to operate at 20 second headways, which yields $y = 180\ trains\ per\ hour$. This number is assumed a reasonable starting point for the rail DRT research.

Concerning the aspect of capacity costs, 'CROW Kengetallen' is used as a source which specifies one average infrastructure price. Each kilometre of track is set at €50 million over a 30 year time period. A station platform of 200 metres costs €650 million, which is €3.25 million per metre of platform.

It could be argued that infrastructure costs in a rail DRT system are lower than in today's supply driven system. All infrastructure currently is dimensioned to support and facilitate the heaviest cargo train that could possible operate. In practise, the majority of trains is lighter and causes less fatigue and wear. Still, the heavy infrastructure demand remains. In a rail DRT system, the homogeneity of the fleet allows for tailoring infrastructure to the highly predictable stress and fatigue characteristics. Metro systems around the world use this approach to optimize maintenance and decrease costs of infrastructure. Nevertheless, the absence of reference material on rail DRT vehicles and technology does not allow for this tailoring to be done yet. Therefore, within the purposes of this thesis, 'CROW Kengetallen' is assumed sufficiently accurate a representation of infrastructure costs.

Recall the assumption that every platform needs a set of low speed switches. They have a length of 15 metre each according to ProRail specifications. One metre of platform length is added per 3 seats in the vehicle. This is based on a comparison to current single deck NS rolling stock, which has 3 seats per metre of vehicle length on average. Please refer to appendix D for an elaborate calculation.

5.2.8 Operational costs

A variety of components contribute to operational costs. Cumulatively, these components can be expressed in a vehicle cost per hour or per (seat) kilometre. The operational costs in the current supply driven system offer a starting point for rail DRT. Nevertheless, the nature of both systems and the vehicles characteristics are vastly different. Several considerations must be made to transform the current operational costs into a prediction for rail DRT. Confidential data on the upcoming computations is included in appendix B. The operational cost indication is based on the advice by drs. Von Königslöw, senior prudential advisor at NS.

The main components in operational costs are interest, depreciation, insurance, maintenance, fees and overhead. The biggest change in costs between a rail DRT system and the current supply driven system is expected to arise due to the different vehicle size. Every individual vehicle has its own engine, control systems and other related components. In a rail DRT system, the ratio of seats to engine and other systems is higher than in the current system. Current ratio is 80 to 200 seats per power unit. In rail DRT at the chosen vehicle size, this would be 24 seats per power unit. Conversely, the engine and related components in rail DRT vehicle are smaller, which partly compensates for the increased engine-to-seat ratio.

Assuming that half the operational costs of rail vehicles are fixed and the other half varies according to vehicle size, it is expected that rail DRT vehicles are Confidential data kilometre compared to current stock. This would be in the order of €0.02 to €0.05 per seat kilometre. The lowest value is used for the base case scenario. The remainder is used in a sensitivity analysis.

5.3 Base case scenario results and analysis

Recall from figure 3.2 the list of output from the model: fleet size, station platform capacity, track capacity, offered seat kilometres and level of service. Naturally, fleet size is expressed as the number of vehicles. Infrastructure capacity may vary among each station and each connecting arc. A fictional network does not allow for benchmarking with an existing case. This eliminates the need to analyse and compare every individual station or arc. Instead, the cumulative infrastructure costs is a relevant output. Concerning level of service, the unit of passenger hours is considered most appropriate.

Table 5.2 and figure 5.9 show the base case scenario results. The right column in the table indicates the difference between the grid and ring/radial network, expressed in a percentage with respect to the grid network. Individual arc and node capacity, as well as flow routing matrices are included in appendix K.

Table 5.2: Base case scenario results.

Parameter	Units	Grid network	Ring/radial network	Difference
Arc costs	*[€1000]*	31.79	33.48	5.31%
Node costs	*[€1000]*	46.41	46.31	-0.21%
Operational costs	*[€1000]*	9.91	10.43	5.33%
Passenger costs	*[€1000]*	47.09	49.08	4.22%
Passenger hours	*[hrs]*	4709	4908	
Fleet size	*[vehicles]*	370	386	
Offered seat kilometres	*[1000 km]*	495.4	521.6	
Share of transferring passengers	*[-]*	9.26%	9.26%	-
*Objective function improvement**	*[€1000]*	-11.19 (-7.6%)	-10.83 (-7.2%)	

**Difference between objective function final value and the objective function value in the initial solution.*

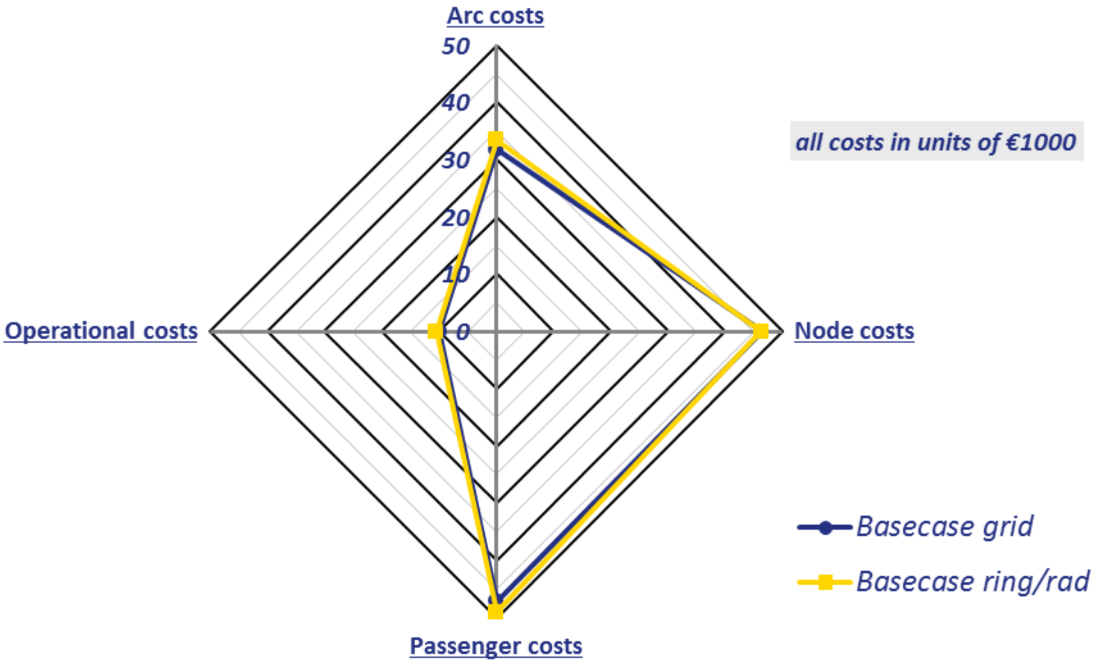


Figure 5.9: Base case results in a radar graph representation.

In general, the cost components in the grid network have lower values compared to their ring/radial counterparts. Closer inspection of the results indicate that this difference cannot be explained directly from physical dissimilarity among the networks. Two factors of influence are identified as the most likely attributors to this phenomenon.

First, there is the availability of equal length route options between most OD-pairs in the grid network as opposed to hardly any in the ring/radial variant. This is illustrated in figure 5.10 which compares the shortest length route options between nodes 12 and 16. In the grid network, flows can often be rerouted at constant mileage, while in the ring/radial network rerouting always comes at a price of increased travel distance. This theory is supported by the detailed results in appendix K, which indicate that flow rerouting is common in the grid network, whereas all vehicles take the shortest route in the ring/radial alternative. Secondly, while average arc length in the grid network is 8.0 kilometres compared to 7.66 in the ring/radial variant, the modal arc length in the grid is smaller (ring/radial: 8.48 and grid: 6.0). Arc capacity is constant along the entire length of an arc. Therefore, a capacity increase is more expensive for longer arcs compared to shorter ones. The longer modal arc length in the ring/radial network may therefore be a factor of influence in its higher capacity costs.

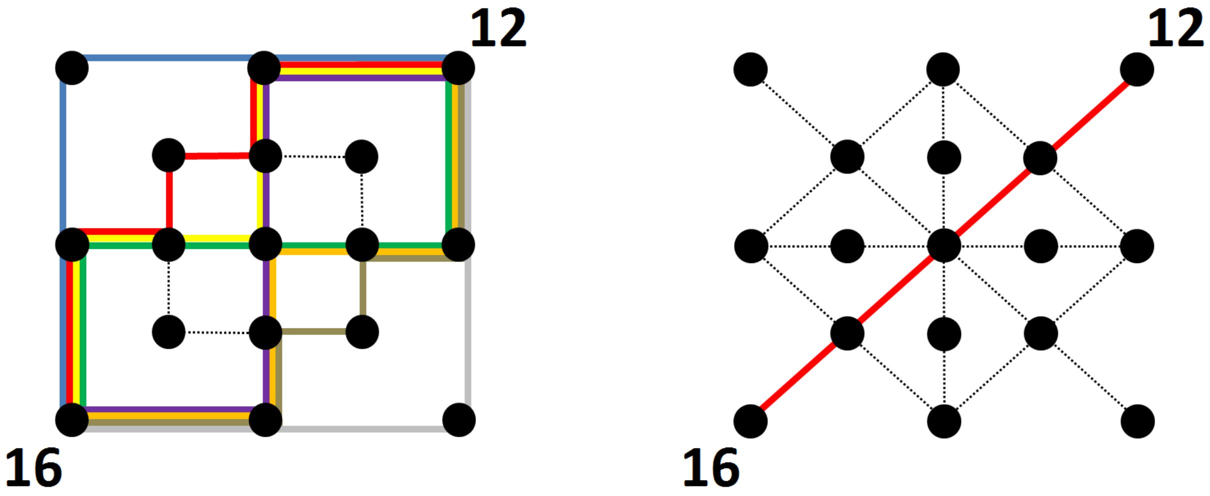


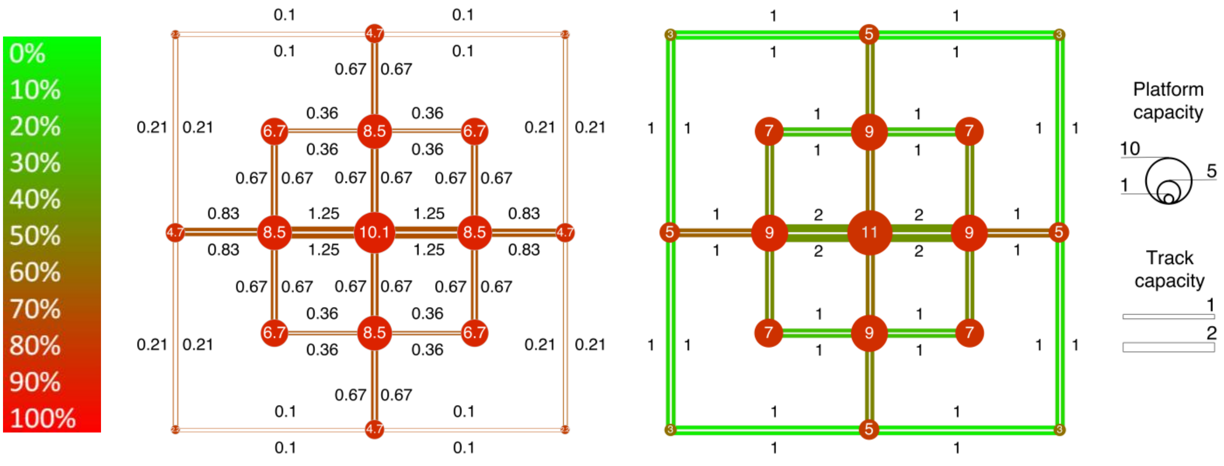
Figure 5.10: Shortest length route options between nodes 12 and 16 in the gird network (left) and ring/radial network.

A noticeable result from the radar graph representation is the relatively small share of operational costs compared to the other components. Given that operational costs relate to offered seat kilometres, one might expect that reduction of vehicle mileage does not have priority. Still, the aspect of passenger costs is what prevents the model from introducing large detours to avoid congested areas. Passenger costs are approximately in balance with infrastructure capacity costs.

The results in appendix K indicate that the vehicle flow distribution over the route alternatives in the grid network is not fully symmetric, while the allocated infrastructure capacity over the network does show symmetry. Again, the vast number of equal length route options (figure 5.10) is considered the most likely cause. The highly symmetric nature of the grid network allows for various flow distributions to exist at equal costs. In other words, the optimal solution in appendix K is not unique. This claim is verified by developing a solution to the rail DRT problem from a different initial solution. The model attains the same objective function value ($1.35 \cdot 10^5$) while the decision variable settings are different than before. Within reasonable time limits it has not been possible to determine the total number of solutions.

An interesting observation is the difference between the initial solution and final solution. Capacity decreases on some arcs, while it increases on others. Ultimately, the arc capacity settles such that the corresponding infrastructure utilization is approximately 70%, up from 65% in the initial solution. Node capacity on the other hand appears to have decreased only. Corresponding infrastructure utilization is rather high, generally in excess of 80%. While this value is beneficial from a financial perspective, one could question the extent to which it can actually be attained in practise and, if the utilization can be truly attained, what will be the effects on service robustness and resilience.

Although the high node capacity utilization can be explained from mathematics, a practical point of view calls for reassessing one major assumption in the model. Waiting time at nodes is determined by queuing theory under the assumption of Poisson arrivals. The assumption holds for high frequency services in general, but there is a particular effect in the heterogeneous DRT system which opposes the assumption. Consider a station where vehicles arrive according to a Poisson process. Bunching effects occur as a result of vehicle interaction caused by differences in service time among dwelling and non-stop vehicles. The bunching effects are expected to increase when multiple low capacity stations exists sequentially. The extent to which the assumption of a Poisson arrival process is violated remains open to debate. In any case, the high capacity utilization must be considered with care.



Unrounded infrastructure capacity *Integer platform and track capacity*

Figure 5.11: Allocated capacity (shown by numbers) and corresponding utilization (shown by colours) in the grid network.

The precursory paragraph discussed the network's capacity utilization. It is close to 70% on most arcs and in excess of 80% for nodes. These values hold for the major part of the network. A visual representation of allocated infrastructure capacity and corresponding utilization in the grid network is provided on the left side of figure 5.11. The figure indicates the low variability in capacity utilization across the network (67% to 72%).

In practise, infrastructure capacity is bound to integer values. Although it was an explicit choice during model development not restrict to integers, it is worthwhile to explore the effects of rounding all infrastructure capacity to the next integer. Corresponding results are visualized on the right side of figure 5.11. All but four arcs have a single track. Only the connections between nodes 1, 5, 9 and vice versa require double track. Hourly arc capacity costs increase to €73 thousand compared to €32 thousand in the unrounded case. Hourly node capacity costs increase to €50 thousand up from €46 thousand. Notably, arc costs are considerably more sensitive to the integer capacity criterion.

Appendix K also provides an overview of the flow distribution over the available route options per OD-pair. Although passenger costs are included in the model objective function, the model does not guarantee an upper bound for travel time on an individual level. One could pose the question if travel time extremes exist. This proves not to be the case. In first place, maximum detour factor is an input. This already ensures that no routes are selected with a travel time in excess of 50% compared to the shortest route based on free flow conditions. Nevertheless, the adjustment of track capacity and flow distribution may still result in lengthy travel times. Given that infrastructure utilization never exceeds 87% anywhere in the network, the corresponding speed reduction and travel time increment is limited.

5.4 Sensitivity analysis with one-at-a-time variation

In chapter 3, 4 and 5.2 it has been suggested to apply a sensitivity analysis for the following input variables: vehicle capacity, track capacity, arc speed-density relation, operational costs, capacity costs and demand distribution. The upcoming sections describe the range over which each of the input parameters may be varied and present the corresponding results. A broader range of input values is applied in case it is judged necessary after assessing the first results, for example if there is no effect on the output within the selected range of input.

The sensitivity analysis approach is a one-factor-at-a-time method. Varying one factor at a time does not allow for identification of correlation and interaction between variables. While the one-factor-at-a-time method is clear and straight forward, it does not cover a global sensitivity analysis. Time and administration constraints limit the possibility to analyse all feasible input scenarios (5760 in total). Hence, a full combinatorial approach is impossible. Instead, the results of the one-factor-at-a-time method are used to develop the most relevant scenarios for further assessment. This is topic of section 5.5.

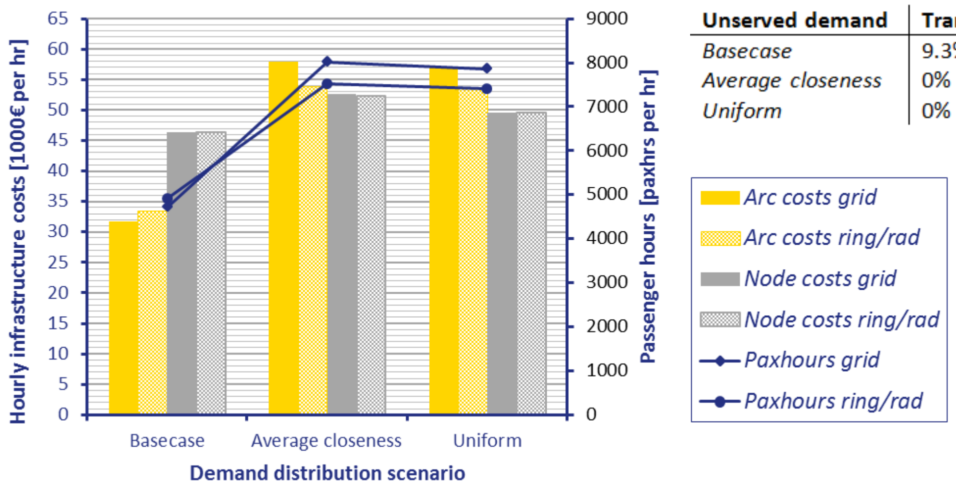
5.4.1 Demand distribution

The base case scenario used a gravity model to distribute passenger demand over the network. On a demand distribution scale from uniform to central, this method would be on the 'central' end of the spectrum. The other extreme point would be a perfect uniform distribution using the reference value of 125 passengers per OD-pair from section 5.2. This uniform case is selected as second demand scenario.

A third option would be in the middle of the distribution scale. The third demand scenario assigns a weight to each node based on the average closeness centrality among the two input networks. This implies that the third scenario is not independent from network connectivity, in contrary to the first two scenarios. Each OD-pair has a scaling factor equal to the product of the origin and destination node's weight. The cumulative demand of 34,000 passengers per hour is distributed over the network by computing the relative share of demand per OD-pair based on the OD-pair's scaling factor. Equations 5-3 and 5-4 apply. The demand per OD-pair is presented in appendix F.

Figure 5.12 presents the output variables of arc costs, node costs and passenger hours for each of the three demand scenarios. Note that the values of passenger hours are connected in the figure for clarity of visualization only. The lines do not represent any interpolation between the scenarios. Most interesting result in the base case scenario is that node costs are distinctly higher than arc costs (over 40%). Conversely, both these infrastructure costs components are fairly equal in the average closeness scenario and uniform demand scenario. Table 5.3 holds the corresponding values.

Generally speaking, the results indicate that infrastructure costs increase when demand is more uniform, with arc costs being affected most. However, one may question the validity of this statement in practical applications by referring to the arc costs' sensitivity to the 'integer capacity criterion', which was discussed in section 5.3 on the precursory page.



Unserved demand	**Transfer**	**No service**
Basecase	9.3%	0%
Average closeness	0%	0%
Uniform	0%	0%

Figure 5.12: Sensitivity of infrastructure costs and passenger hours to demand distribution.

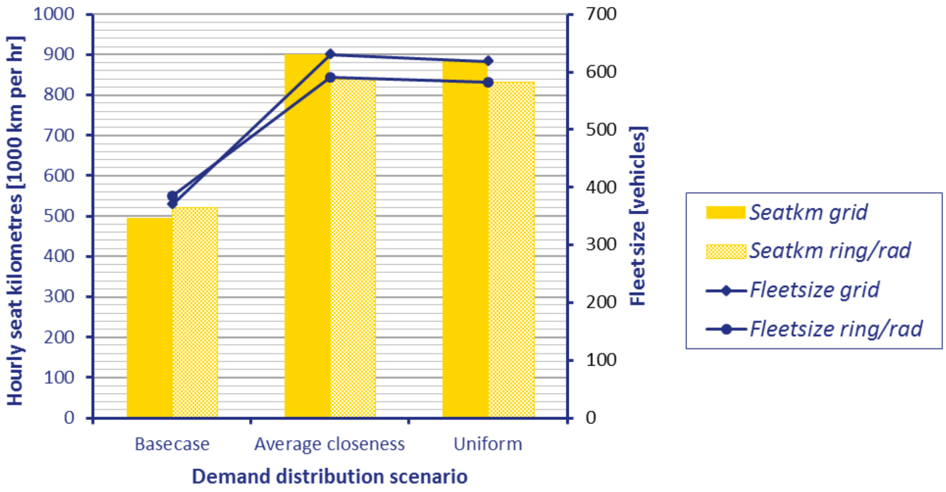


Figure 5.13: Sensitivity of seat kilometres and fleet size to demand distribution.

Figure 5.13 holds the results of the two remaining performance indicators: fleet size and offered seat kilometres. Again there is a major increase in all values from the base case towards the other two scenarios. Furthermore, the ring/radial network has lower operational costs in the average closeness scenario and uniform scenario, while the grid network is cheaper in the base case. These phenomena relate to the network structures. The selected grid network offers shorter arc length in the centre of the network, which coincides with the demand's centre of gravity in the base case. Conversely, the ring/radial network has relatively better connectivity and a constant arc length towards the outskirts. Therefore, the ring/radial network performs better when demand is distributed more uniformly. The grid network's ability to reroute flows at constant route length does not compensate, because the shortest route between many distant OD-pairs simply is longer in the grid network.

Finally, it must be noted that the increase in passenger hours from base case to uniform demand scenario is attributed partly to the simultaneous decrease in unserved demand. The model assumes that all passengers are served free of transfers as long as there is sufficient demand. Passengers on low yield OD-pairs require to transfer. These customers are not included in the passenger hour count, because their number is assumed to be small. In the base case scenario 9.3% of the passengers needs to transfer. The majority of this group travels between the most distant OD-pairs. In the more uniform demand scenarios, the share of unsatisfied demand reduces to zero, hence introducing many long distance passengers to the network. A more fair comparison of passenger costs in this case would be the ratio of passenger kilometres to passenger hours, as a measure of service effectiveness. The results in table 5.3 indicate an improvement of average passenger travel speed in the more uniform demand scenarios, while there is no significant difference among the performance of the two networks.

Table 5.3: Sensitivity of the objective function components and related parameters to demand distribution.

		Base case		Average closeness		Uniform	
Parameter	**Units**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**
Arc costs	*[€1000]*	31.79	33.48	57.89	53.87	56.93	53.44
Node costs	*[€1000]*	46.41	46.31	52.66	52.36	49.52	49.49
Operational costs	*[€1000]*	9.91	10.43	18.04	16.79	17.74	16.65
Passenger costs	*[€1000]*	47.09	49.08	80.13	75.16	78.59	74.05
Fleet size	*[vehicles]*	370	386	630	591	618	582
Offered seat kilometres	*[1000 km]*	495.4	521.6	902.1	839.4	887.1	832.5
Service effectiveness	*[Paxkm/paxhrs]*	74	74	79	78	79	79

5.4.2 *Vehicle capacity*

The input variable of vehicle size can be varied over a broad range of values. The number of scenarios can be limited by increasing the step size between each consecutive parameter setting. The following seating capacities are considered:

- Small: 12
- Medium: 24 (base case)
- Large: 48
- Very large: 96

The medium vehicle size of 24 seats is the reference value from the base case. Increasing the vehicle size by a factor 2 results in a capacity of 48 seats. This is comparable to an average bus. Applying a factor 2 again creates a vehicle of 96 seats. Current NS intercity trains are composed of units which have 80 to 100 seats. Hence, the very large vehicle of 96 seats corresponds to one unit in the today's system. Finally, the smallest vehicle is found by applying the common factor of 2 in opposite direction: 12 seats, comparable to a van.

Figure 5.14 presents the sensitivity of arc costs, node costs and passenger hours to vehicle size. Again, the line connecting the passenger hour values in each scenario is for visualization purposes only and does not represent any interpolation. The most notable effect shown by figure 5.14 is the decrease of infrastructure costs with increasing vehicle size. Table 5.4 holds the corresponding data. Arc costs shows a significant reduction of almost 90% from the 12-seat scenario to the 96-seat scenario. Node costs decrease by 'only' 75%. Clearly, the reduction in required platform capacity is compensated partly by the increase in platform length associated with larger vehicles. Any difference in cost components between the grid network and ring/radial network appear to diminish with increasing vehicle size.

The major reduction of infrastructure costs from the 12-seat scenario to the 96-seat scenario cannot be assessed without considering the effects of unserved demand. Given a constant threshold value of 3.0 departures per hour for an OD-pair to be served at all, the share of passengers which require to transfer goes up from 1.7% in the small vehicle scenario to 35% in the very large vehicle scenario. The latter percentage is no longer a negligibly small part of the passengers. It is suggested for section 5.5 to study the results of a simultaneous increase in vehicle size and a decrease in service frequency threshold such as to overcome the deficiency of very large shares of unserved demand.

Unserved demand	Transfer	No service
Small (12 seats)	1.7%	0%
Base case (24 seats)	9.3%	0%
Large (48 seats)	24%	0%
Very large (96 seats)	35%	0%

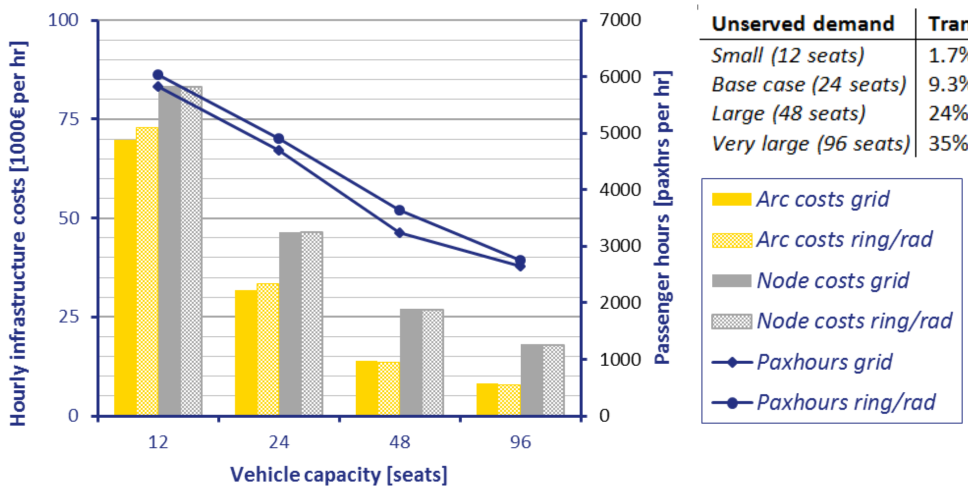


Figure 5.14: Sensitivity of infrastructure costs and passenger hours to vehicle capacity.

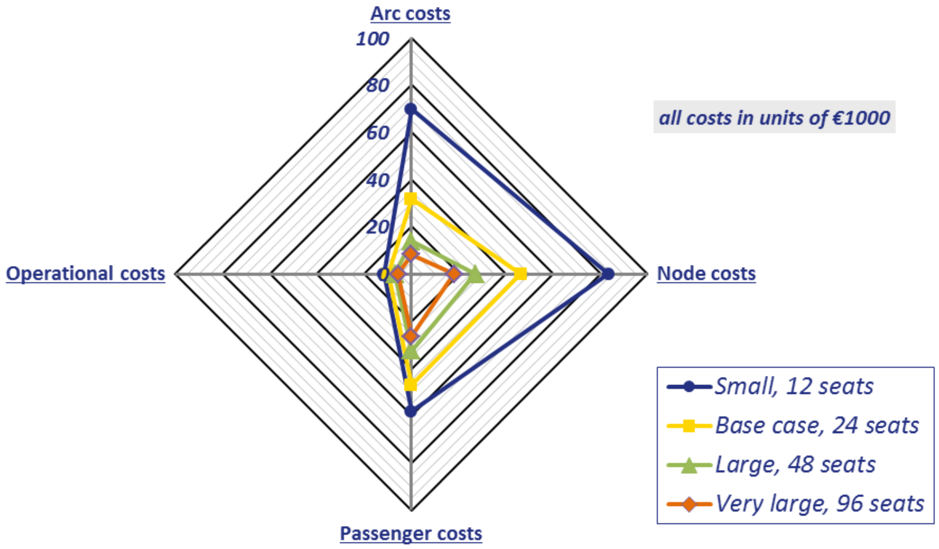


Figure 5.15: Radar graph representation of the sensitivity of all cost components to vehicle capacity.

While the infrastructure costs and passenger costs appear to be quite sensitive to changing vehicle size according to figure 5.14, the operational costs hardly show only half as much a change. The decrease in operational costs between the 12-seat scenario and 96-seat scenario is just under 50%, compared to much higher percentages in the other cost components. This is shown graphically in figure 5.15. The results raise the question if a constant price per seat kilometre among all vehicle sizes is justifiable. In fact, section 5.3 argued that rail DRT vehicles are more expensive than conventional trains because of their smaller size. According to the same analogy, it is worthwhile to explore the effect of simultaneously increasing costs per seat kilometre while decreasing vehicle size. This is studied in section 5.5. Figure 5.16 shows the sensitivity of fleet size and offered seat kilometres to vehicle size. The results are in line with the effects addressed earlier.

A remarkable outcome from table 5.4 is the relatively constant service effectiveness over the very large-, large- and base case scenario, whilst the 12-seat scenario has a lower average operational speed. This effect is explained from the larger fleet size, increased number of seat kilometres and slightly higher infrastructure utilization. Apparently, in the small vehicle scenario, the costs of adding infrastructure to increase operational speed up to the same level as in the other scenarios does not outweigh the benefits of saving passenger costs.

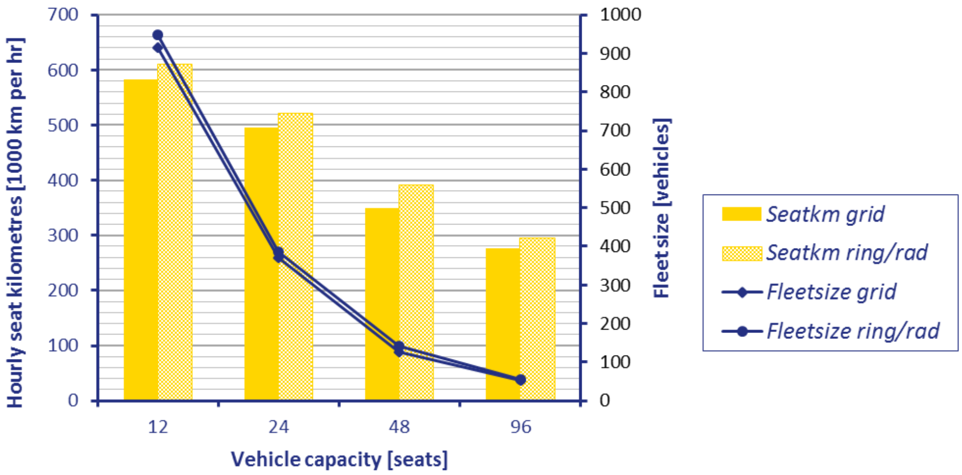


Figure 5.16: Sensitivity of seat kilometres and fleet size to vehicle capacity.

Table 5.4: Sensitivity of the objective function components and related parameters to vehicle size. Please refer to table 5.3 for the base case results (vehicle capacity of 24 seats).

		Small (12)		Large (48)		Very large (96)	
Parameter	**Units**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**
Arc costs	*[€1000]*	69.84	72.92	13.95	13.50	8.33	7.75
Node costs	*[€1000]*	83.34	83.22	26.99	26.78	18.14	17.98
Operational costs	*[€1000]*	11.67	12.18	6.97	7.80	5.53	5.89
Passenger costs	*[€1000]*	58.21	60.33	32.44	36.35	26.52	27.46
Fleet size	*[vehicles]*	915	948	127	143	52	54
Offered seat kilometres	*[1000 km]*	583.5	609.2	348.7	390.1	276.6	294.6
Service effectiveness	*[Paxkm/paxhrs]*	70	71	75	75	73	75

5.4.3 *Operational costs*

In accordance to NS advice, the operational costs per seat kilometre are varied over a range from €0.01 to €0.05. Confidential data while the highest value represents the upper bound suggested by NS. Given a base case of €0.02, the other intermediate values between lower and upper boundary are found by interpolation:

Confidential data

- €0.01
- €0.02
- €0.03
- €0.04
- €0.05

Results are simple, yet remarkable. There is no change in any of the cost components but operational costs. Moreover, vehicle routing and allocated infrastructure capacity do not vary either. The radar graph representation of the results in figure 5.17 shows this peculiar outcome. Bar charts and other visualization is omitted, because it shows a flat trend overall.

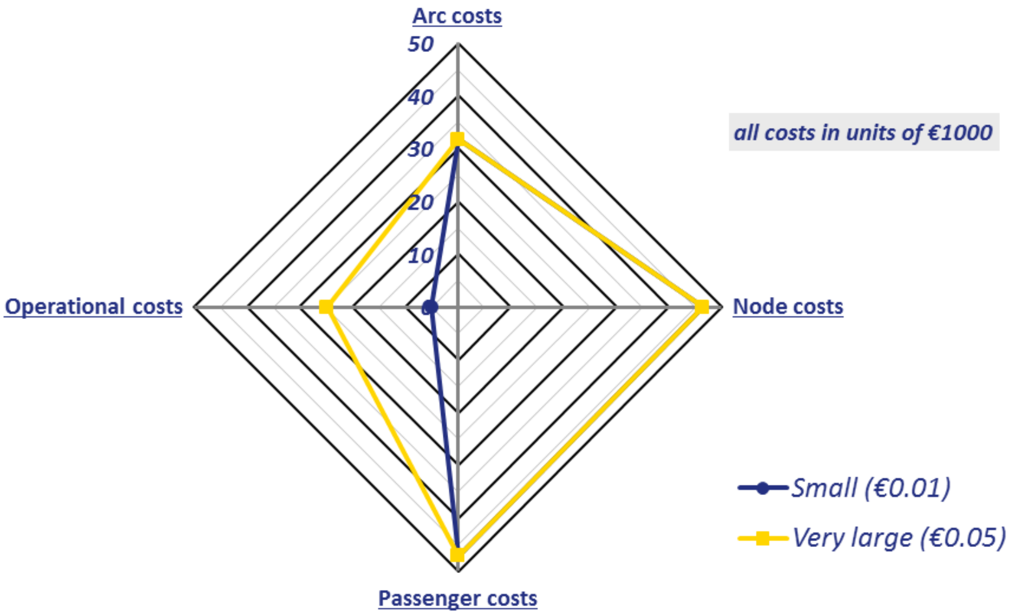


Figure 5.17: Radar graph representation of the sensitivity of all cost components to unit operational costs in the grid network.

Only when the costs per seat kilometre are in excess of €0.30, there will be changes in the decision variables. This value appears to coincide with the point where operational costs start to exceed the other cost components in the objective function. Only once the operational costs are sufficiently high to allow for a fruitful trade-off between the costs components, there will be flow rerouting and infrastructure adjustments. In the grid network, this 'tipping point' is at a slightly lower seat kilometre price, because the grid offers more possibilities for rerouting like discussed in section 5.4.1. It may be stated that the sensitivity of results to changes in unit operational costs are negligible within the range of unit operational cost values suggested by NS.

5.4.4 *Capacity costs*

The range of variation of infrastructure capacity costs is not very trivial to define, because of the dual nature. In this thesis, infrastructure is composed of railway tracks and station platforms. One could opt for changing the unit capacity costs of both simultaneously or either one at the time. Recall from section 5.2 that most uncertainty in capacity costs is associated with the possible benefits from tailoring track infrastructure to the homogenous fleet and load predictability in rail DRT. From that perspective, it would be best to vary track infrastructure costs more prominently than platform capacity costs. On the other hand, one could question if it is justifiable to make profound changes to the ratio of track costs to platform costs. Therefore, in this sensitivity analysis, one single discount factor will be applied to both the infrastructure capacity cost elements simultaneously. Given that capacity costs reductions are more likely in rail DRT than cost increase, a larger range of positive discount applies:

- Major reduction: 25% discount
- Minor reduction: 10% discount
- Base case: 0 % discount
- Minor increase: 10% more expensive

Results of the sensitivity analysis into infrastructure costs are displayed in table 5.5. A Radar graph representation of the sensitivity of all cost components in the grid network is provided in figure 5.18. In case of an increase in unit infrastructure costs, it is expected that the model uses its optimization capabilities such that the cumulative increase in costs over all components is as low as possible. For example, a more expensive unit infrastructure costs may result in less allocated capacity at the expensive of higher passenger costs. Indeed this is the exact description of the results in table 5.5. In case of the 10% unit infrastructure cost increase, the fleet size goes up by 1.5% compared to the base case, while mileage is constant. This implies that no vehicle flow is rerouted. Instead, a lower average speed shows that infrastructure utilization must have increased because of the efforts to save on infrastructure (0.8% arc capacity reduction and 1.1% node capacity reduction). On the other hand, passenger hours are up by 1.5%. These percentages are equal in both network structures.

Table 5.5: Sensitivity of the objective function components and related parameters to infrastructure costs. Please refer to table 5.3 for the base case results.

		25% discount		10% discount		10% cost increase	
Parameter	**Units**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**
Arc costs	*[€1000]*	24.89	26.29	29.05	30.46	34.63	36.46
Change from base case		-22%	-22%	-8.6%	-9.0%	+8.9%	+8.9%
Node costs	*[€1000]*	35.80	36.58	42.13	42.03	50.67	50.57
Change from base case		-23%	-21%	-9.2%	-9.2%	+9.2%	+9.2%
Operational costs	*[€1000]*	9.92	10.47	9.94	10.43	9.91	10.43
Passenger costs	*[€1000]*	45.29	48.42	46.50	48.35	47.77	49.78
Change from base case		-3.8%	-1.3%	-1.3%	-1.5%	+1.3%	+1.4%
Fleet size	*[vehicles]*	356	380	365	380	375	391
Offered seat kilometres	*[1000 km]*	495.8	523.7	496.9	521.6	495.4	521.6
Service effectiveness	*[Paxkm/paxhrs]*	77	76	75	76	73	73

Given the absence of flow rerouting in all infrastructure cost scenarios, the element of operational costs is insensitive to changes in unit infrastructure costs. This is emphasised by the radar graph representation of the results in figure 5.18. This particular phenomenon points the attention of the reader onto the effects of one assumption made during model development. Operational costs depend on vehicle mileage only. Average operational speed, vehicle hours or fleet size are not taken into account. In the scenarios of varying unit infrastructure costs, a constant operational cost is attained at various levels of vehicle hours (5% difference between the two extreme scenarios on either end of the spectrum). One could therefore question the validity of the assumption.

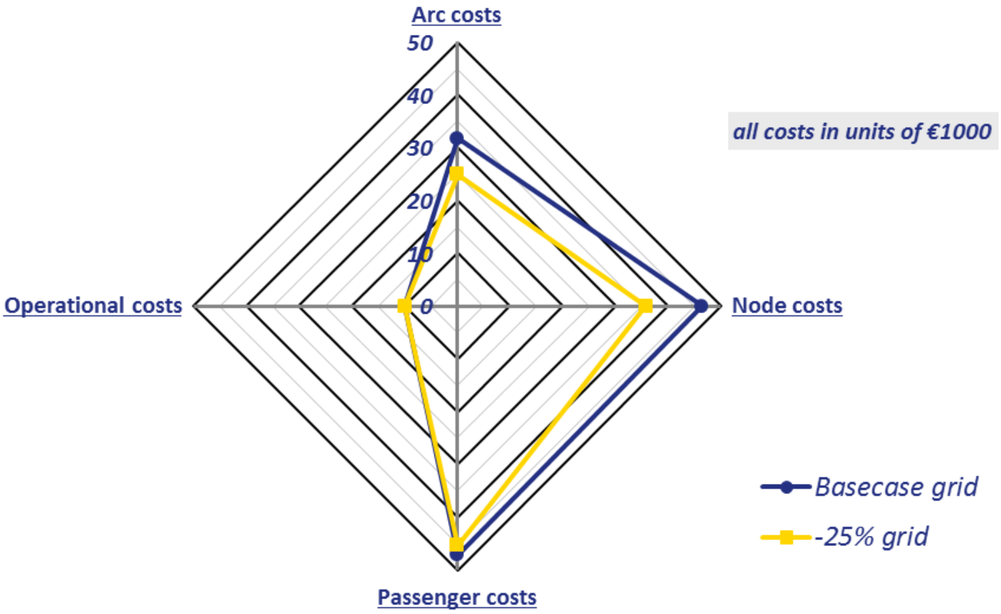


Figure 5.18: Radar graph representation of the sensitivity of all cost components to infrastructure costs in the grid network.

In the scenario of 10% and 25% reduction of infrastructure costs there is a slight increase in offered seat kilometres in the grid network, which indicates the occurrence of some vehicle flow rerouting. Nevertheless, the difference between the scenarios is marginal (less than three-tenth of a percent). This confirms the behaviour seen in earlier paragraphs that vehicle rerouting is rare in any case. A much bigger effect is observed in passenger costs, which decrease between 1.3% and 3.8% depending on the network and scenario. In other words, when unit infrastructure costs are lower, the system will add infrastructure capacity in order to increase operational speed and consequently reduce passenger costs. While the unit cost increase by 10% did not influence the grid and ring/radial network differently, the 25% discount scenario does. Cumulative reduction in the objective function is larger in the grid network (16.8% vs 12.6% in the ring/radial network). There is no solid underlying cause which can be identified. It is noted however, that the component of node costs contributes most to this difference between the networks.

5.4.5 Speed-density relation

The logistic arc speed-density relation is governed by two parameters: α and β. These cannot be selected independently from each other. The parameter values are determined by solving a set of equations. The equations are obtained from setting the speed reduction factors to preference at an intensity to capacity ratio of 0.8 and 1.0. In the base case, the values of the speed reduction factors were derived from a UIC advice and a comparison to automated car systems. Two different cases are added in the sensitivity analysis.

First, consider a situation of a mixed fleet. Although the rail DRT system in this thesis is assumed to have a homogeneous fleet, it would technically be possible to operate mixed size vehicles. Properties and characteristics are likely size dependent. Differences in acceleration and deceleration decrease minimum headway and consequently reduce the effectiveness of capacity utilization. The logistic speed-density relation will then be closer to regular traffic. The corresponding speed reduction factors are set according to the 'jam scenario'.

Second, consider a situation in which the automated system is highly capable of reducing headways and utilizing capacity efficiently. This will be referred to as the 'easy-flow scenario'. The selected speed reduction factors are displayed hereafter.

- Easy-flow scenario
$$\begin{cases} f_v(\varphi = 0.8) = 0.90 \\ f_v(\varphi = 1.0) = 0.35 \end{cases} \quad \alpha = -14.08,\ \beta = 0.96$$
- Base case
$$\begin{cases} f_v(\varphi = 0.8) = 0.7 \\ f_v(\varphi = 1.0) = 0.2 \end{cases} \quad \alpha = -11.17,\ \beta = 0.88$$
- Jam scenario
$$\begin{cases} f_v(\varphi = 0.8) = 0.50 \\ f_v(\varphi = 1.0) = 0.05 \end{cases} \quad \alpha = -8.96, \quad \beta = 0.75$$

Results of the sensitivity analysis into the arc speed-density relation are displayed in figure 5.19 and table 5.6. Offered seat kilometres are constant throughout the scenarios. It indicates that no vehicle flow rerouting occurs. This result is a logical consequence of the fact that all arcs are affected evenly by the changes in α and β. In popular terms 'you can't avoid the jam' by rerouting. However, arc capacity does increase in the jam scenario to compensate for the 'loss' in passenger hours. The arc capacity costs are up by 18.3%, while the passenger costs increase by 'only' 6.6%. The drop in average operational speed is limited from 74 kilometres per hour in the base case scenario to 69 kilometres per hour in the jam scenario. Conversely, in the easy-flow scenario, capacity costs decrease by 11.2% and passenger costs are down by 3.3%. These effects are equal in both the grid network and ring/radial network.

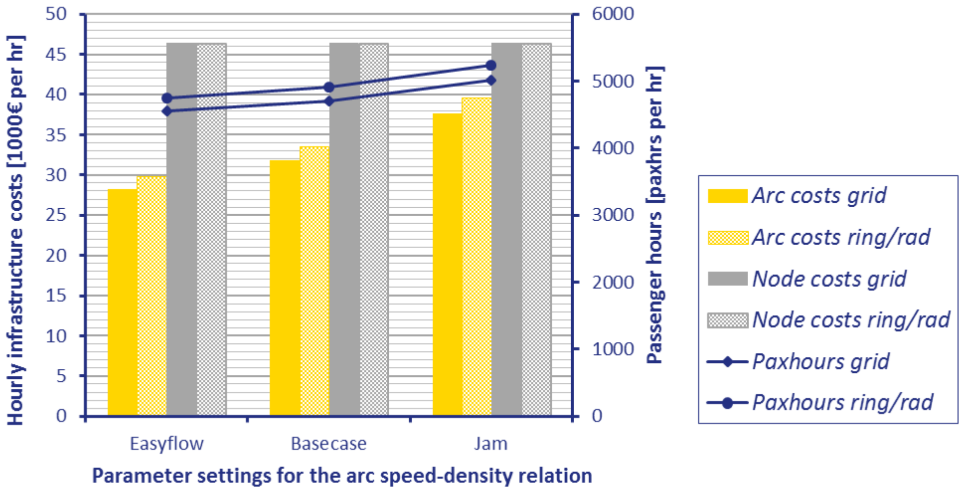


Figure 5.19: Sensitivity of infrastructure costs and passenger hours to the arc speed-density relation.

Node costs are unaffected, because the speed-density relation applies to the arcs only. However, the changes in arc costs can be considered significant. Considering that earlier results showed that an increase in vehicle size corresponds to a decrease of infrastructure costs, one may pose the question if it is an option to use larger vehicles in the jam scenario to (partly) compensate for the increased arc costs? Furthermore, the question arises if it is fair and justifiable to still have a track capacity of 180 vehicles per hour in the jam scenario. Therefore, the simultaneous adjustment of vehicle size, track capacity and arc speed-density parameters is a suggestion for study in section 5.5.

Table 5.6: Sensitivity of the objective function components and related parameters to the arc speed-density relation.

		Easy flow scenario		Base case		Jam scenario	
Parameter	**Units**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**
Arc costs	*[€1000]*	28.24	29.74	31.79	33.48	37.60	39.59
Node costs	*[€1000]*	46.41	46.31	46.41	46.31	46.41	46.31
Operational costs	*[€1000]*	9.91	10.43	9.91	10.43	9.91	10.43
Passenger costs	*[€1000]*	45.54	47.44	47.09	49.08	50.18	52.33
Fleet size	*[vehicles]*	358	373	370	386	394	411
Offered seat kilometres	*[1000 km]*	495.4	521.6	495.4	521.6	495.4	521.6
Service effectiveness	*[Paxkm/paxhrs]*	76	77	74	74	69	70

5.4.6 *Track capacity*

The final variable to be included in the sensitivity analysis is track capacity. The base case scenario defines $y = 180\ [vehicles/hr]$. This number is very high compared to existing systems. Therefore, the sensitivity analysis will only include lower values. Three alternatives are suggested. The most conservative value is the maximum frequency in classical heavy rail with ERTMS signalling: 30 trains per hour. A somewhat higher value can be found in automated metro systems, such as Paris' Line 14: 45 trains per hour. Finally, the highest throughput is obtained from the 2015 study by Haverkamp & Maat. Their operational model indicated 120 vehicles per hour during peak hours on the most busy segments of the network.

Low:	30 $[vehicles/hr]$.
Medium:	45 $[vehicles/hr]$.
High:	120 $[vehicles/hr]$.
Base case:	180 $[vehicles/hr]$.

Results of the sensitivity analysis into track capacity are displayed in figures 5.20, 5.21 and table 5.7.

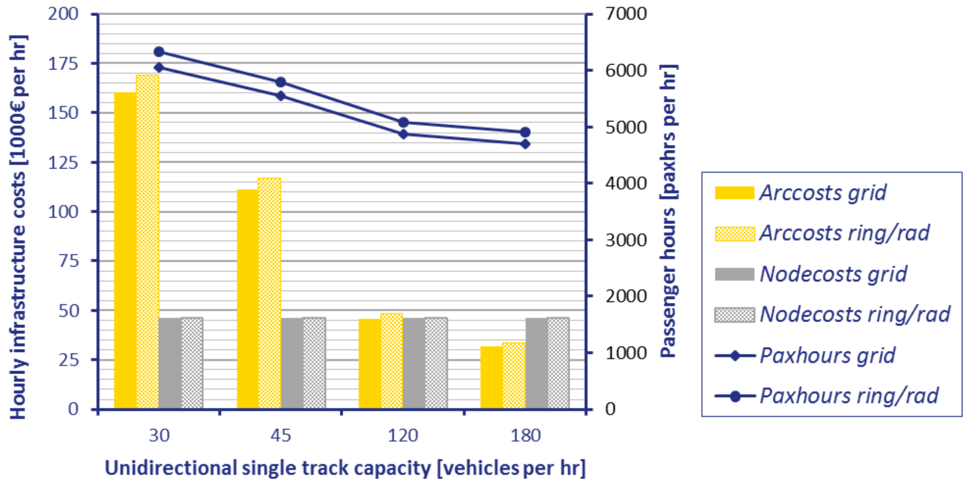


Figure 5.20: Sensitivity of infrastructure costs and passenger hours to track capacity.

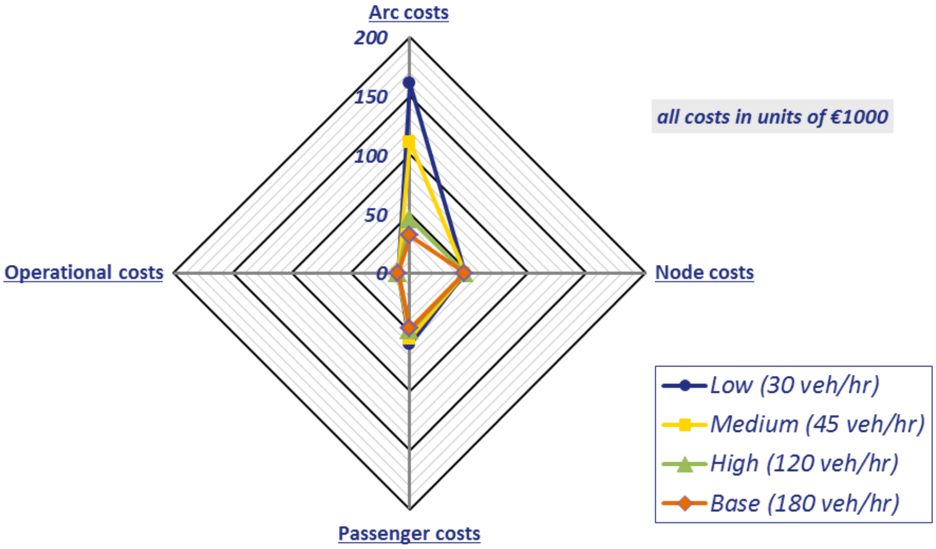


Figure 5.21: Radar graph representation of the sensitivity of all cost components to track capacity in the grid network.

The cost component which is affected most by a change in track capacity is arc costs. In the scenario of 30 vehicles per hour per single track, arc costs increase by over 400% compared to the base case, while passenger costs are up by 'only' 29%. Node costs and operational costs are not affected. This is shown prominently by the radar graph in figure 5.21. The absence of vehicle flow rerouting results in a constant value for operational costs and node costs. The vast difference between the other two components can be explained from the linear relation of arc costs to allocated capacity and the logistic relation of passenger costs to allocated capacity.

The results indicate that arc properties are more critical to a well-functioning rail DRT system than node properties or operational properties alike. Moreover, figure 5.20 shows that only at a track capacity of 120 vehicles per hour, the components of node costs and arc costs are approximately equal. At lower track capacity, arc costs is the dominant element. Although a low arc capacity (less than 120 vehicles per hour) does not make it impossible to operate rail DRT, one must be aware that a low arc capacity leads to a very costly system with limited operational speed.

Table 5.7: Sensitivity of the objective function components and related parameters to track capacity. Please refer to table 5.3 for the base case results.

		30 vehicles/hr		45 vehicles/hr		120 vehicles/hr	
Parameter	**Units**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**	**Grid**	**Ring/rad**
Arc costs	*[€1000]*	160.5	169.0	111.0	116.9	45.76	48.18
Change from base case		+405%	+405%	+250%	+250%	+45%	+45%
Node costs	*[€1000]*	46.41	46.31	46.41	46.31	46.41	46.31
Operational costs	*[€1000]*	9.91	10.43	9.91	10.43	9.91	10.43
Passenger costs	*[€1000]*	60.56	63.26	55.59	58.03	48.67	50.74
Change from base case		+29%	+29%	+18%	+18%	+3%	+3%
Fleet size	*[vehicles]*	476	497	437	456	382	399
Offered seat kilometres	*[1000 km]*	495.4	521.6	495.4	521.6	495.4	521.6
Service effectiveness	*[Paxkm/paxhrs]*	57	58	62	63	71	72

5.5 Alternative scenarios

Three suggestions for additional scenarios were proposed during assessment of results in the one-variable-at-a-time sensitivity analysis. Each of those is described in further detail hereafter. The base case scenario remains the starting point for all upcoming scenarios. Changes in input variables are discussed with respect to the base case. Considering that the differences between the results in the grid network and ring/radial network were marginal in the precursory sensitivity analyses, it is considered justifiable from the perspective of running time constraints, to limit the upcoming analysis to the grid network only.

5.5.1 Vehicle size and operational costs

It was noted that a change in vehicle size should come with a corresponding adaption of operational costs per seat kilometre. After all, the very definition and determination of operational costs started from the assumption that smaller rail vehicles come at higher costs, because the seat-to-engine ratio is lower compared to current rolling stock. The smallest DRT vehicle should have highest operational costs and the largest vehicle is associated with lowest costs. In similar analogy to appendix B, the following operational cost values are selected for each of the vehicle sizes:

- Small: 12 seats, €0.08 per seat kilometre
- Medium: 24 seats, €0.02 per seat kilometre (base case)
- Large: 48 seats, €0.015 per seat kilometre
- Very large: 96 seats, €0.0125 per seat kilometre

Results are shown in table 5.8. For every scenario, table 5.8 has an additional column holding the results from the one-variable-at-a-time analysis during which the unit operational costs were constant at €0.02 per seat kilometre. First observations show that there are hardly any changes from the standard €0.02 case, apart from the element of operational costs itself. In other words, the change in unit operational costs has not had major influences on any of the other costs components during the optimization process. Some very minor effects include small scale rerouting in the 48-seat scenario. This is proven by the slight increase in vehicle kilometres and fleet size, which apparently allowed for lower node costs.

Given the absence of major changes between this combinatorial sensitivity analysis of vehicle capacity and operational costs and the one-factor-at-a-time sensitivity analysis into vehicle capacity only, the reader is kindly referred to figure 5.14 for a visualization of results. The radar graph does require updating. It is included in figure 5.22 and shows that a simultaneous change in seat kilometre price and unit operational costs has most influence on the component of operational costs. Results are therefore in line with the earlier one-variable-at-a-time sensitivity analysis into operational costs and vehicle size. Special crossover effects have not been identified.

Table 5.8: Sensitivity of the objective function components and related parameters in the grid network to combined changes in vehicle size and unit operational costs. Please refer to table 5.3 for the base case results.

		Small (12)		Large (48)		Very large (96)	
Parameter	**Units**	**€0.02**	**€0.08**	**€0.02**	**€0.015**	**€0.02**	**€0.0125**
Arc costs	*[€1000]*	69.84	69.84	13.95	14.287	8.33	8.31
Node costs	*[€1000]*	83.34	83.34	26.99	26.70	18.14	18.14
Operational costs	*[€1000]*	11.67	46.68	6.97	5.25	5.53	3.46
Passenger costs	*[€1000]*	58.21	58.21	32.44	32.84	26.52	26.52
Fleet size	*[vehicles]*	915	915	127	129	52	52
Offered seat kilometres	*[1000 km]*	583.5	583.5	348.7	350.2	276.6	276.6
Service effectiveness	*[Paxkm/paxhrs]*	70	70	75	75	73	73

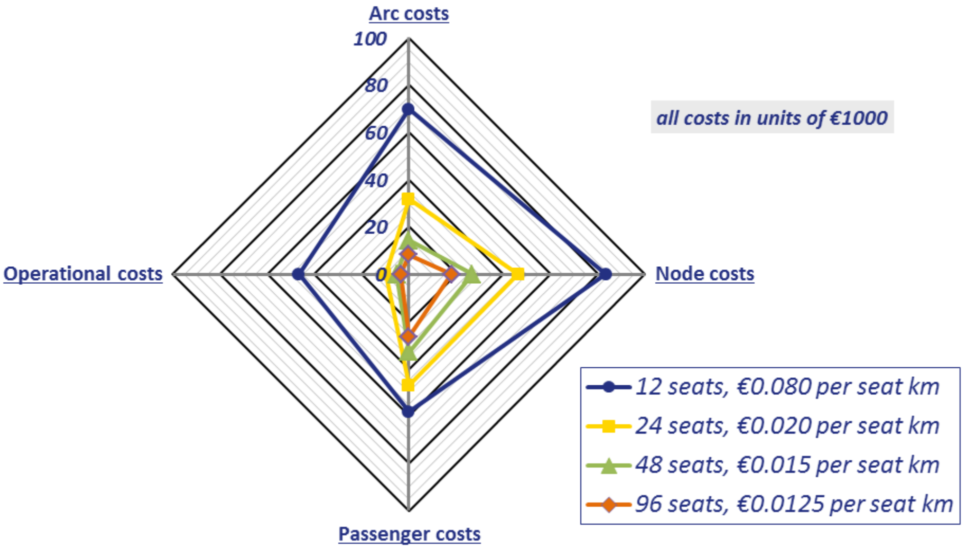


Figure 5.22: Radar graph representation of the sensitivity of all cost components in the grid network to combined changes in vehicle size and unit operational costs.

5.5.2 Vehicle size and service frequency threshold

It was suggested earlier to study the effects of a simultaneous increase in vehicle size and a decrease in service frequency threshold such as to overcome the system deficiency of large shares of unserved demand. The vehicles sizes in the following scenarios are equal to those studied in the one-variable-at-a-time sensitivity analysis. The largest vehicle is associated with a frequency threshold of one departure per hour. The threshold values for smaller vehicles are set such that the minimum capacity of 96 seats per hour is obtained in all scenarios. In this way, the share of unserved demand will be equal in all cases (12%). Note that the base case scenario is not included here.

Small:	12 seats, minimum of 8 departures per hour
Medium:	24 seats, minimum of 4 departures per hour
Large:	48 seats, minimum of 2 departures per hour
Very large:	96 seats, minimum of 1 departure per hour

Results are shown in table 5.9. An interesting development is apparent. While the served passenger demand is equal in all scenarios, the quantity of offered seat kilometres is distinctly different, shown by figure 5.24. The 96 seat scenario has 7% less seat kilometres than the 48-seat case, while the other scenarios are in between. Given that load factor and passenger demand is constant by definition (input), the results suggest that vehicle rerouting is more common in some scenarios than in others. Indeed this is proven by the detailed decision variable data (available at request due to the size of the data). Equal distribution of vehicle flow over the various route options is rather common in the 96-seat scenario, while the 24-seat scenario has almost all vehicles take the shortest route. Naturally, one could pose the practical question if any rerouting is possible when an OD-pair has only one departure per hour. Nevertheless, this is a consequence of the decision not to use integer numbers rather than a property of the DRT system.

Another clear effect is the significant increase in require infrastructure capacity when using smaller vehicles. Capacity cost are more than five times as high for arcs and three times as high for nodes in the 12-seat scenario compared to the 96-seat scenario. The difference among the two components is the fact that node capacity has a relation to platform length, which in itself is related to vehicle size. On the other hand, arc capacity properties are completely independent from vehicle length.

Table 5.9: Sensitivity of the objective function components and related parameters in the grid network to combined changes in vehicle size and service frequency threshold.

Parameter	Units	Small (12) ≥8 per hour	Medium (24) ≥4 per hour	Large (48) ≥2 per hour	Very large(96) ≥1 per hour
Arc costs	*[€1000]*	54.96	29.57	17.68	10.60
Node costs	*[€1000]*	74.30	44.89	31.52	24.13
Operational costs	*[€1000]*	9.18	9.22	9.50	8.88
Passenger costs	*[€1000]*	46.94	44.13	43.04	40.56
Fleet size	*[vehicles]*	738	347	169	79
Offered seat kilometres	*[1000 km]*	459.1	460.8	475.1	443.8
Service effectiveness	*[Paxkm/paxhrs]*	68	73	77	77
Cost effectiveness	*[€ / paxkm]*	0.58	0.40	0.31	0.27

The effects on infrastructure capacity requirements among the scenarios are visible in operational speed as well. The 12-seat scenario is distinctly slower than the 96-seat alternative. This also relates to passenger hours which are not constant over the scenarios despite the demand itself being equal (shown by figure 5.23).

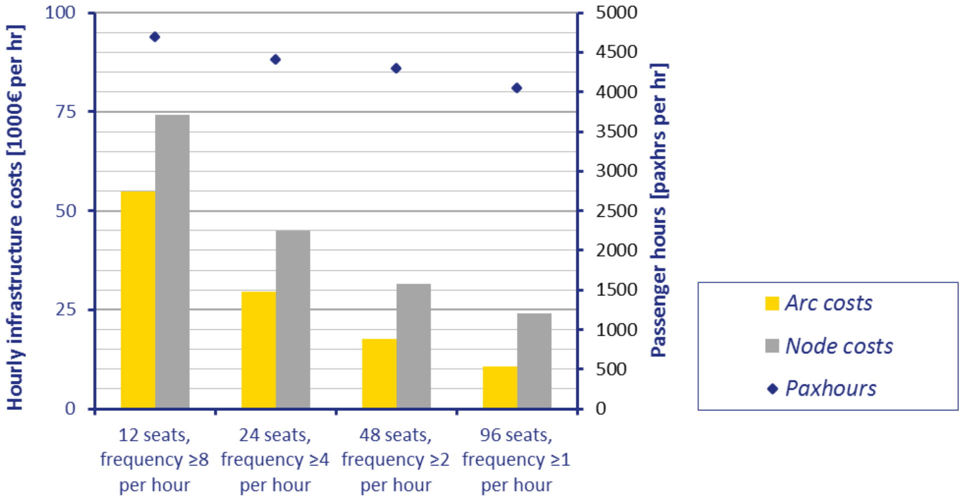


Figure 5.23: Sensitivity of infrastructure costs and passenger hours to combined changes in vehicle size and service frequency threshold.

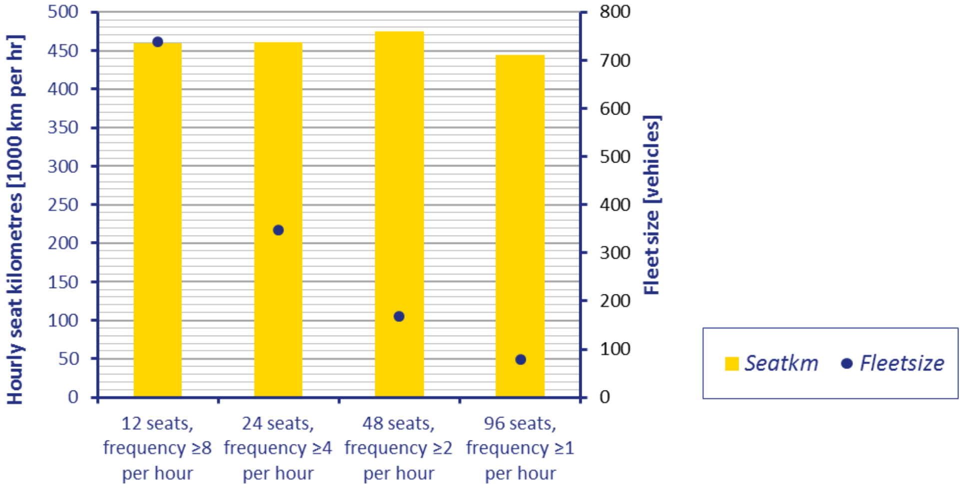


Figure 5.24: Sensitivity of seat kilometres and fleet size to combined changes in vehicle size and service frequency threshold.

It must be noted though that waiting time is not included in the passenger hour count (because it does not affect the optimization process since waiting time depends on the input variables of vehicle size and load factor only). Therefore, the small vehicle scenarios may still be preferred for customer satisfaction. For illustrative purposes, the cumulative value of all four cost components included in the model, have been expressed per passenger kilometre in table 5.9. It is clear that the large vehicle scenario is more cost-effective.

Stating a vehicle size of preference remains a decision for the operator. Nevertheless, the exponential nature of required infrastructure at smaller vehicle size is an important concern. In any case, the increase in costs with decreasing vehicle size are considerably less extreme when selecting the minimum service frequency in consideration with the vehicle size, as shown by a comparison of table 5.4 and 5.9.

5.5.3 Vehicle size and arc speed-density relation

The parameter settings in the jam scenario of the arc speed-density relation were associated with a significant increase in arc costs. Conversely, the sensitivity analysis into vehicle size showed that increasing vehicle size comes with decreasing capacity costs. It raises the question if the jam scenario effects can be compensated by adapting vehicle size. The following options are considered:

- Small: 12 seats, easy-flow scenario
- Medium: 24 seats, base case scenario
- Large: 48 seats, jam scenario

Results are displayed in table 5.10. Indeed the use of larger vehicles in the jam scenario could improve overall costs, likewise that smaller vehicles better fit the easy flow scenario. Arc costs and passenger costs appear to be the only elements which are effected significantly. However , the exact sensitivity of all components to the various arc speed-density scenarios is impossible to state explicitly. After all, the chosen scenario parameters remain somewhat arbitrary. A more accurate understanding of rail DRT vehicles and technology must be available first. Then, the rail DRT model can be used to assess these more grounded numbers.

Table 5.10: Sensitivity of the objective function components and related parameters in the grid network to combined changes in vehicle size and arc speed-density function parameters.

		Small (12)		Medium (24)	Large (48)	
Parameter	**Units**	**Easy flow**	**Base case**	**Base case**	**Base case**	**Jam**
Arc costs	*[€1000]*	63.34	69.84	31.79	13.95	16.09
Change from base case		-9%				+15%
Node costs	*[€1000]*	82.88	83.34	46.41	26.99	26.72
Change from base case		-1%				+1%
Operational costs	*[€1000]*	11.71	11.67	9.91	6.97	6.98
Change from base case		0%				0%
Passenger costs	*[€1000]*	56.18	58.21	47.09	32.44	34.30
Change from base case		-3%				+6%
Fleet size	*[vehicles]*	883	915	370	127	135
Offered seat kilometres	*[1000 km]*	585.6	583.5	495.4	348.7	348.9
Service effectiveness	*[Paxkm/paxhrs]*	73	70	74	75	71
Cost effectiveness	*[€ / paxkm]*	0.52	0.55	0.39	0.33	0.34

6. Case study

In order for results to be most useful for NS and to allow for greater feeling and affinity with the output, a case study has been conducted which considers part of the actual NS network. The following chapter is devoted to that case study. First, the case selection and description is presented in section 6.1. Results are shown and discussed in section 6.2.

6.1 Case selection and description

The case study concerns only a part of the railway network in The Netherlands. The following paragraphs first explain the choice not to assess the entire Dutch network as a whole. Sequentially, the case selection process is discussed. The section finalises with a description and visualization of the case study area.

6.1.1 Scope and motivation

The Dutch railway network cannot be assessed as a whole. This is motivated by two arguments. First, the size and volume of the network is too comprehensive a convenience case study for the available model. Secondly, one could question the validity of the input passenger data from specific parts of the network. These issues are elaborated upon in the upcoming paragraphs.

Section 3.3.4 presented a list of model requirements. This included the capability to handle a network of 30 nodes, 60 arcs and 35,000 hourly passenger request. While the model has been tested to show compliance with these requirements, the model's exact envelope of application has not been explored in detail. Nevertheless, the numerical experiments in chapter 5 showed a strong correlation between various input variable settings and model running time. In particular, network and demand size, as well as the number of route options per OD-pair were of significant influence on running time. In order to restrict the case study running time within practical bounds, it is decided that the case study network must obey the aforementioned boundaries on network and demand size. Consequently, the Dutch network cannot be assessed as a whole, since it holds over 400 nodes and carries Confidential data passengers just on the main lines during the busiest peak hour.

NS holds the exclusive rights to offer train services on the main line network. Several decentralized railways are operated by other service providers. Their passenger data is unavailable, creating 'gaps' in the passenger demand data. This is particularly challenging in areas where multiple operators serve the same stations, such as Arnhem Velperpoort – Arnhem Centraal – Elst, Venlo - Blerick and, since very recently, a variety of stations in the province of Limburg. To ensure data validity and reliability, the selected case study shall only contain stations served by NS exclusively.

Given that the Dutch railway network will not be assessed as a whole, a sub network shall be used instead. It is assumed that this network segment operates as a rail DRT system separately from the remainder of the network. Any issues arising from this assumption are discussed in section 6.1.2. However, in order to limit adverse consequences of the assumption, the nature of the chosen sub network is preferably such that is can truly be considered a standalone network. Combining all case study requirements from section 6.1.1, results in the following overview:

i. All stations are served exclusively by NS to ensure availability and validity of data.
ii. The network and demand size are at most 30 nodes, 60 arcs and 35,000 hourly passenger request.
iii. The network allows for rerouting and hence it is more complex than a simple line.
iv. The network has at least three places of diverging or converging branches.
v. There is as little interaction as possible with the railway network outside the scope.

6.1.2 *Case selection, description and visualization*

The selected case is the railway network in the province of Noord-Holland, north of the North Sea Channel, shown in figures 6.1 and 6.2. This specific sub network is the best available option within the Dutch railway system which fits the five criteria from section 6.1.1. Other options which have been considered are the railway lines north of Zwolle, the area enclosed south of Dordrecht and west of Breda, a segment of the ‘Oude Lijn’ from Amsterdam to The Hague, the star network around Utrecht, the triangle between Rotterdam, The Hague and Gouda and the area bounded by Breda, Utrecht and Eindhoven. Each option and its characteristics are shown on a map in appendix I. Neither one of the alternatives but the selected area meets all five criteria, as indicated by table 6.1.

Table 6.1: Case selection based on the criteria from section 6.1.1. Criteria are shown to be fully met (green, +), mostly met (yellow, 0) or violated (red, -). Please refer to appendix I for the underlying data.

Case	Criteria *i.*	Criteria *ii.*	Criteria *iii.*	Criteria *iv.*	Criteria *v.*
Triangle Zwolle, Leeuwarden, Groningen	-	+	+	-	0
Area south of Dordrecht, west of Breda	0	+	0	-	-
‘Oude Lijn’ from A’dam to The Hague	+	-	-	-	-
Noord-Holland above North Sea Channel	+	+	+	+	+
Star network around Utrecht	0	-	-	0	-
Triangle Rotterdam, The Hague, Gouda	+	+	0	-	-
Area bounded by Breda, Utrecht, E’hoven	+	0	-	+	0

6.1.3 *Case description and visualization*

The sub network of choice holds the following lines: Amsterdam Centraal – Den Helder, Zaandam – Enkhuizen and Heerhugowaard – Hoorn. Although the addition of the branch from Uitgeest via Haarlem to Amsterdam would add more route options and network complexity to the case, this part of the network is omitted, because it would introduce a vast amount of assumptions about passenger routing on several busy routes such as Amsterdam – Haarlem – Leiden – Rotterdam. This is elaborated upon in greater detail on the next page. Note that the train service from Amsterdam to Schiphol Airport is not included in the selected subnetwork.

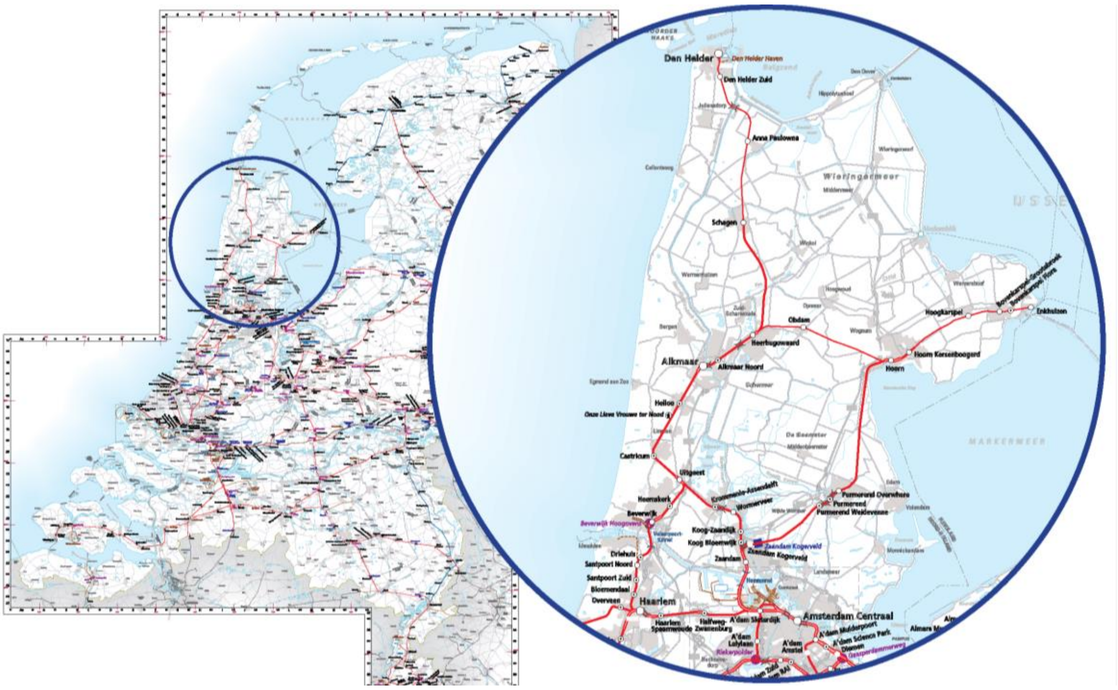


Figure 6.1: Selected sub network in the case study in respect to the Dutch railway system as a whole.

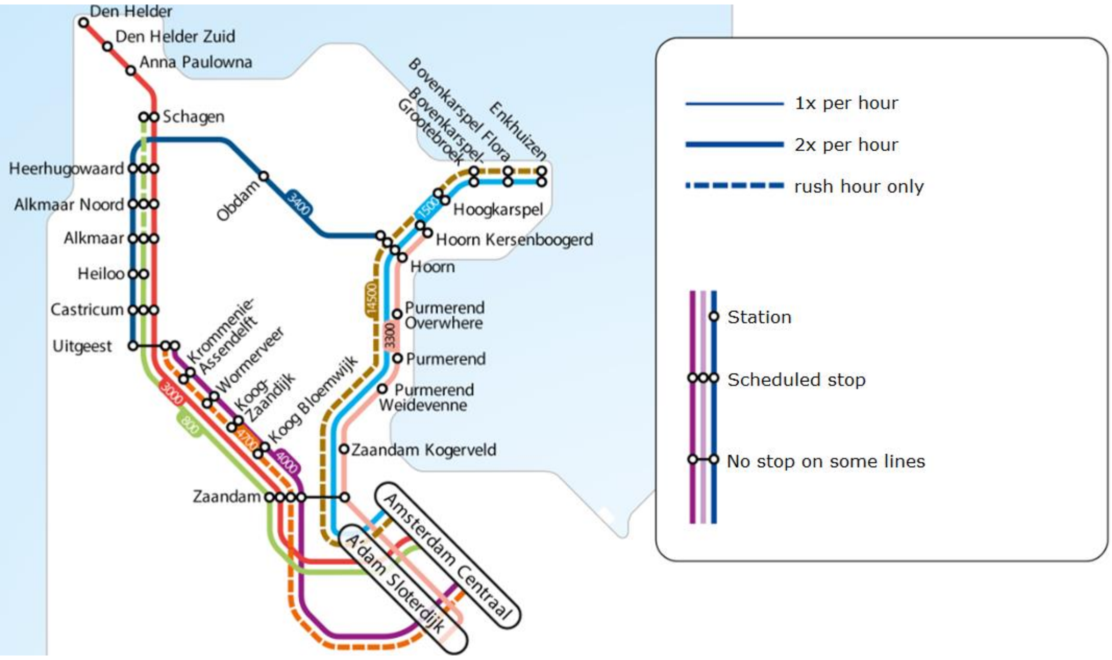


Figure 6.2: Train services in the selected sub network in the 2016 timetable.

Whenever there are multiple stations where the DRT network and supply driven network connect, one must assume a certain transfer station between the DRT and supply driven system for every passenger with an origin in one area and a destination in the other. Depending on the quantity of transferring passengers, these assumptions may have consequences for the flows of passengers and vehicles in the system. In the network of choice, the potential interchange stations are Uitgeest, Amsterdam Sloterdijk and Amsterdam Centraal. For purposes of simplicity, passengers are assumed to transfer either at Uitgeest or Amsterdam Centraal, so Sloterdijk is left out of scope. Uitgeest is considered to be the preferred option for all passengers travelling to or from the area bounded by Leiden, Sloterdijk, and Uitgeest on one end; and towards or from a station north of Wormerveer and west of Hoorn on the other end. All other transfers are assumed to take place in Amsterdam.

Passenger demand is obtained from OV-Chipkaart measurements on a regular office day in 2015. In accordance to section 3.3.2, demand is not adjusted for any possible effects caused by introducing DRT service. The level of detail available from the Chipkaart is a 30 minute time period. The model requires hourly units, so the cumulative value over two periods is used. Morning and evening rush hour are considered separately, according to figure 3.3. Minimum service frequency is 1.0 departures per hour. Please refer to section 5.2.5 for an elaborate explanation about this input variable setting.

Figures 6.3 and 6.4 visualize the demand pattern during the morning rush hour. Figure 6.3 includes all demand, while 6.4 is limited to the OD-pairs which remain after the minimum service frequency threshold has been applied. The difference between figures 6.3 and 6.4 shows that even in demand-responsive transport, there are discrepancies between passenger demand and service supply, at least given the definition of DRT in this thesis. The station of Zaandam Kogerveld is not served at all, indicated by the absence of any connecting service arcs in figure 6.4. It is suggested to run a scenario which includes almost all demand by setting the minimum service frequency to 0.1. This corresponds to one train per rush hour period, which would be the absolute minimum service possible.

The demand visualization shows the area’s focus on Amsterdam as a prime destination. Regionally, the cities of Alkmaar, Hoorn and Zaandam are attractive destinations. In the current definition of rail DRT, the case study’s demand pattern will result in many dwelling vehicles in the aforementioned locations and high numbers of through-going vehicles at all other places, except termini of course.

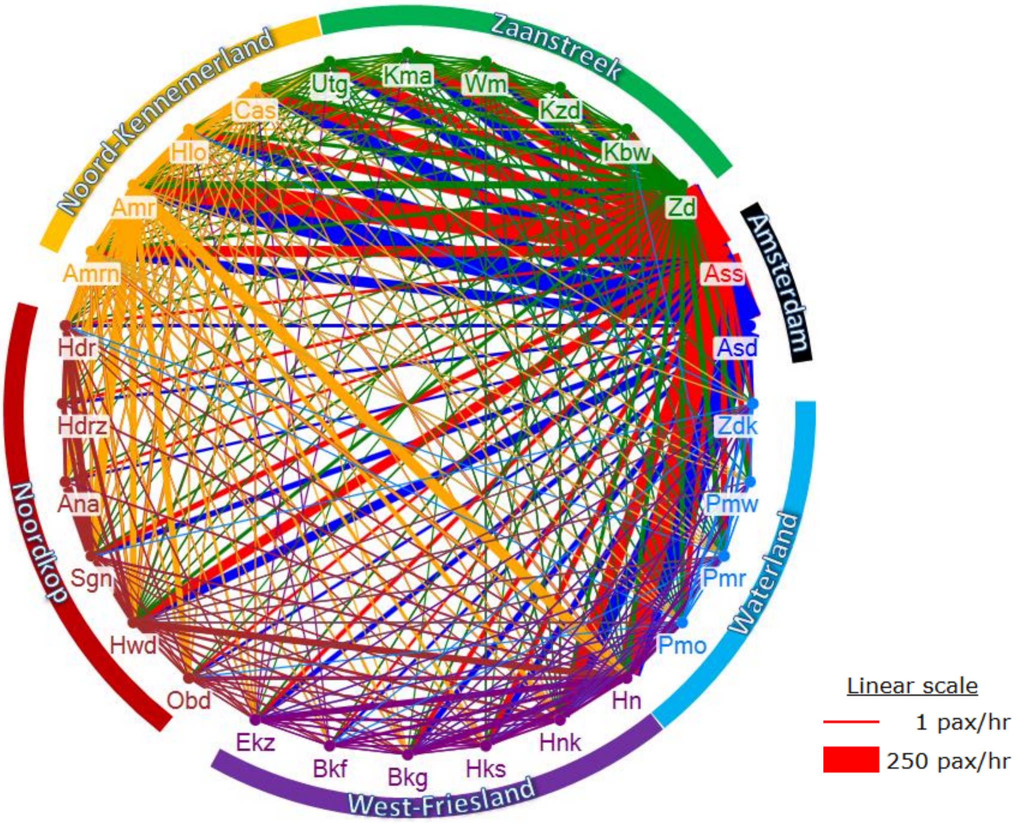


Figure 6.3: Demand visualization in the case study area during the morning rush hour.

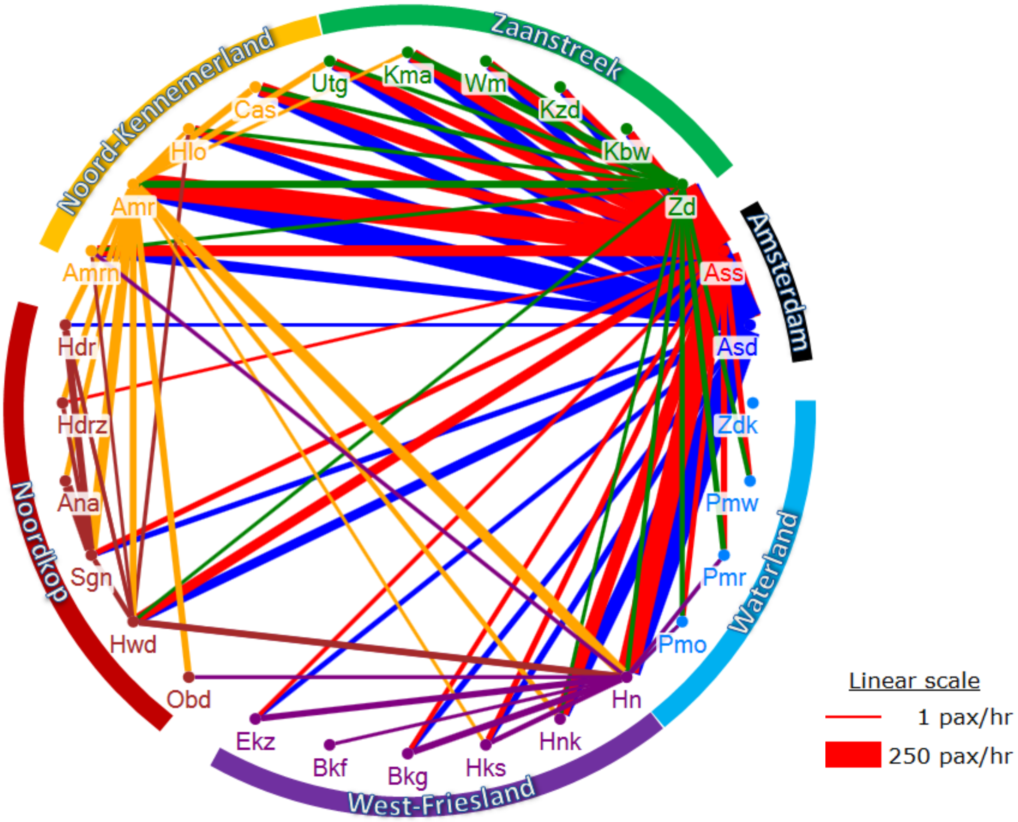


Figure 6.4: Demand visualization in the case study area during the morning rush hour after applying the minimum service frequency threshold of 1.0 departure per hour, or in passenger numbers, 17 passengers per hour. The station of Zaandam Kogerveld (Zdk) is not served at all, indicated by the disconnected node.

An important network characteristic is inter-station distance. Defining inter-station distance is less trivial than expected at first sight. At top level, one could use the public NS price-distance map which contains inter-station distances of all Dutch stations, rounded to integer kilometres. However, this map does not represent the actual distances between stations. Rather, it is adapted to fit with NS price policy. A more accurate measure of inter-station distance is ProRail's map of timetable node locations. Each station is considered a node of zero length, connected by links of certain length representing the inter-station distance. Of course, stations have some finite length, even platform dependent. In certain stations, platforms are aligned asymmetrically or staggered. Such level of detail would only be required in microscopic models. ProRail's timetable node map suffices for the selected macroscopic model.

Network characteristics and demand pattern in the case study have been defined and described now. All remaining input parameters are equal to the base case scenario in the numerical experiments, displayed in table 5.1. The reader is kindly referred to section 5.2 for an elaborate explanation about the base case scenario. Two variables from the base case need specific attention here: track capacity and vehicle size. First, track capacity is significantly higher than in conventional train systems: 180 vehicles per hour per single direction track. While the numerical experiments in chapter 5 already studied the rail DRT system's sensitivity to this input variable, it is worthwhile to repeat the sensitivity analysis in the case study to create a more practical understanding of the results and the impact thereof. Secondly, vehicle size is assessed again for similar reasons.

The following scenarios will be considered in the case study (base case values are shown in italics):

- Minimum hourly service frequency threshold: *1.0* and 0.1
- Track capacity: 30, 60, 120, 150 and *180* vehicles per hour
- Vehicle size: 12, *24*, 48 and 96 seats

Note that the range of input variables in the track capacity sensitivity analysis is slightly different than the range applied in the numerical experiments in chapter 5. This change has been adopted to ensure good interpretability of results, because the sensitivity analysis now has equally sized steps.

6.2 Results and analysis

The case study results are presented and discussed separately for each of the three scenario scopes listed above. The base case scenario itself is discussed in general first.

6.2.1 Base case scenario results

Results are grouped into three areas: general network properties, allocated infrastructure capacity and utilization, and level of service. First, table 6.2 shows the general network properties. Figure 6.5 visualises the results from table 6.2. Figure 6.6 visualises the infrastructure utilization associated with the case study results.

Table 6.2 indicates that passenger costs are the biggest element out of the four cost components. Arc and node capacity costs are more similar, while operational costs are lower. Fleet size in the rail DRT network in Noord-Holland is close to 200 vehicles according to table 6.2. A comparison with the 2015 study by Haverkamp & Maat shows a significant difference. Their prediction for the same network was in the order of magnitude of 600. This vast difference is explained from several underlying assumptions. The current research uses a constant vehicle load factor, while the other study had a varying value which was typically lower. Furthermore, this thesis allows demand not to be served under certain conditions, while the other study had full demand satisfaction as a hard constraint. Finally, the 2015 study was more conservative in vehicle utilization, because the system needed to comply with certain service guarantees such as a maximum waiting time after making a reservation and the system needed to adapt to demand in real time.

Table 6.2: Case study results in the base case scenario, expressed in terms of objective function components and related parameters.

Parameter	**Units**	**Value**
Arc costs	*[€1000]*	17.94
Node costs	*[€1000]*	14.61
Operational costs	*[€1000]*	5.07
Passenger costs	*[€1000]*	24.32
Fleet size	*[vehicles]*	191
Offered seat kilometres	*[1000 km]*	253.6
Unserved demand	*[-]*	4%
Share of transfers	*[-]*	13%
Service effectiveness	*[Paxkm/paxhrs]*	73
Cost effectiveness	*[€ / paxkm]*	0.35

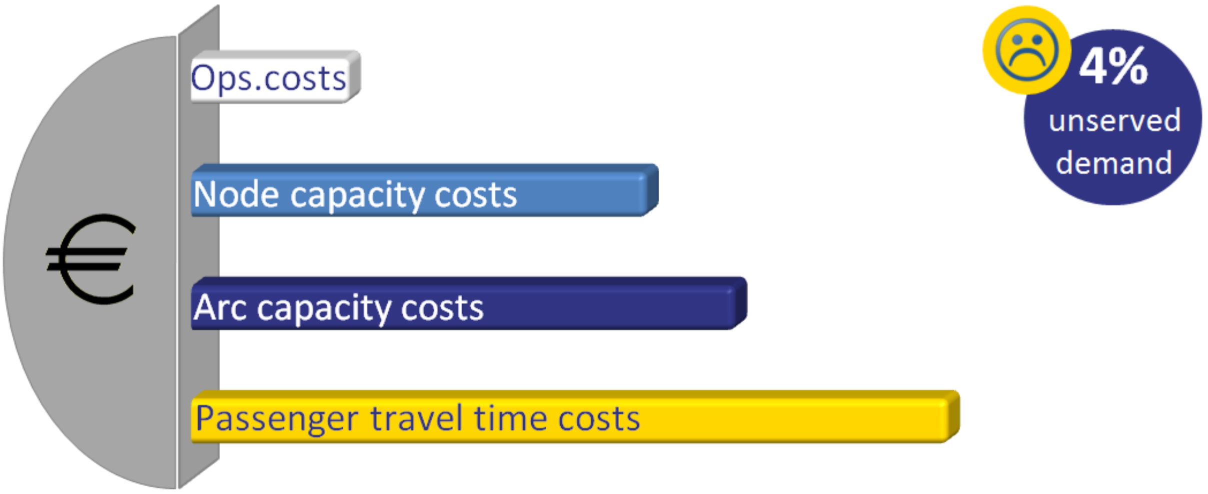


Figure 6.5: Visualization of the case study results in the base case scenario.

Table 6.3 and 6.4 show the allocated infrastructure capacity per arc or node and the corresponding infrastructure utilization. Platform capacity is relatively small for many nodes. Some stations require two platforms, like today. Only the busier stations of Alkmaar, Hoorn, Zaandam, Amsterdam Centraal and Sloterdijk need more platforms. Several stations do not even require two platforms. This is somewhat inconvenient for bidirectional operations. Moreover, it reminds to be critical about the model formulation and the assumptions enclosed within it, for this case in particular the possible violation of the Poisson arrival assumption, which was addressed in section 5.3.

Double track infrastructure is necessary only on the crowded stretch from Amsterdam Sloterdijk to Wormerveer. Single track (per direction) is sufficient on the remainder of the network. This is a very positive result, since the heterogeneity of the rail DRT system could have called for more capacity. Note that the results are symmetric. When assessing the morning or evening rush hour separately, the nature of the passenger demand in the case study area results in asymmetric arc capacity allocation. In practical terms, this leaves room for optimization of infrastructure usage. For example, rather than having two tracks per direction, it might be possible to have only three tracks, with two of them being used in the dominant peak hour direction.

Infrastructure utilization calculations are based upon rounding the allocated infrastructure capacity to integer numbers. However, the model uses continuous variables, so there is a large discrepancy between the model's output arc capacity costs (17,951) and the rounded arc capacity costs (61,494). Similarly for node capacity costs, the model computes 14,610, while the rounded value is 21,602.

Table 6.3: Allocated platform capacity per node and corresponding infrastructure utilization in the case study for the base case scenario. Platform capacity ('s') is expressed in the number of platforms required at that node. Utilization can only be computed for one single time period. The table contains the morning rush hour data.

Node	s	util.	Node	s	util.	Node	s	util.	Node	s	util.
Amr	3	0.64	Cas	2	0.37	Hnk	1	0.49	Pmr	1	0.34
Amrn	1	0.42	Ekz	1	0.18	Hwd	2	0.33	Pmw	1	0.29
Ana	1	0.20	Hdr	1	0.26	Kbw	1	0.66	Sgn	1	0.37
Asd	5	0.73	Hdrz	1	0.14	Kma	2	0.42	Utg	2	0.30
Ass	5	0.74	Hks	1	0.25	Kzd	1	0.64	Wm	1	0.73
Bkf	1	0.04	Hlo	1	0.46	Obd	1	0.16	Zd	3	0.59
Bkg	1	0.20	Hn	3	0.48	Pmo	1	0.31	Zdk	1	0.21

Table 6.4: Allocated capacity per arc and corresponding infrastructure utilization in the case study for the base case scenario. Arc capacity ('c') is expressed in the number of tracks required on that arc. Utilization can only be computed for one single time period. The table contains the morning rush hour data.

Arc		c	Util.	Arc		c	Util.
Amr	Amrn	1	0.07	Hwd	Amrn	1	0.24
Amr	Hlo	1	0.32	Hwd	Obd	1	0.06
Amrn	Amr	1	0.31	Hwd	Sgn	1	0.03
Amrn	Hwd	1	0.07	Kbw	Kzd	2	0.10
Ana	Hdrz	1	0.02	Kbw	Zd	2	0.39
Ana	Sgn	1	0.11	Kma	Utg	1	0.14
Asd	Ass	1	0.28	Kma	Wm	1	0.63
Ass	Asd	1	0.63	Kzd	Kbw	2	0.37
Ass	Zd	2	0.17	Kzd	Wm	2	0.09
Bkf	Bkg	1	0.04	Obd	Hn	1	0.06
Bkf	Ekz	1	0.01	Obd	Hwd	1	0.11
Bkg	Bkf	1	0.01	Pmo	Hn	1	0.06
Bkg	Hks	1	0.09	Pmo	Pmr	1	0.33
Cas	Hlo	1	0.14	Pmr	Pmo	1	0.06
Cas	Utg	1	0.47	Pmr	Pmw	1	0.35
Ekz	Bkf	1	0.04	Pmw	Pmr	1	0.05
Hdr	Hdrz	1	0.04	Pmw	Zdk	1	0.37
Hdrz	Ana	1	0.07	Sgn	Ana	1	0.02
Hdrz	Hdr	1	0.02	Sgn	Hwd	1	0.12
Hks	Bkg	1	0.01	Utg	Cas	1	0.14
Hks	Hnk	1	0.14	Utg	Kma	1	0.54
Hlo	Amr	1	0.15	Wm	Kma	1	0.17
Hlo	Cas	1	0.38	Wm	Kzd	2	0.35
Hn	Hnk	1	0.02	Zd	Ass	2	0.59
Hn	Obd	1	0.09	Zd	Kbw	2	0.10
Hn	Pmo	1	0.31	Zd	Zdk	1	0.05
Hnk	Hks	1	0.01	Zdk	Pmw	1	0.05
Hnk	Hn	1	0.23	Zdk	Zd	1	0.37

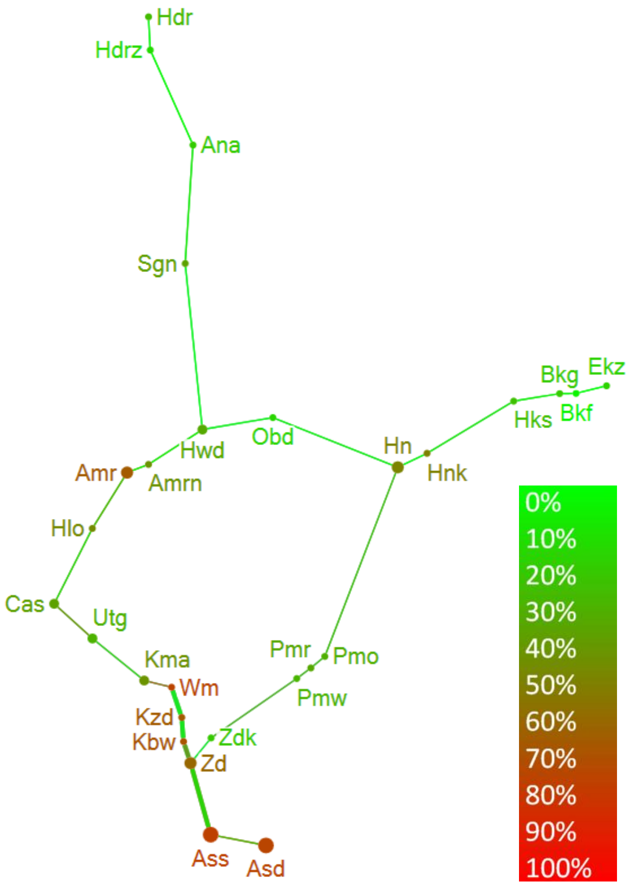


Figure 6.6: Visualization of allocated infrastructure capacity (shown by the size of the lines and circles) and corresponding utilization (shown by colours) in the case study for the base case scenario.

From the infrastructure and operational perspective, the viewpoint now shifts towards level of service. Table 6.5 shows the travel time and service frequency of the five busiest, five quietest and five random OD-pairs of the case study area in the morning rush hour. It benchmarks the rail DRT system to the 2016 time table in the current system, using the fastest available travel option. Results for the full case study area are included in appendix J.

Table 6.5: Comparison of travel time in minutes on the five busiest, five quietest and five random OD-pairs of the case study area in the morning rush hour. Shortest travel time per OD-pair is underlined.

	Demand	Rail DRT		2016 Time table	
OD-pair	**[pax/hr]**	**Travel time [min]**	**Hourly frequency**	**Travel time [min]**	**Hourly frequency**
Zd – Asd	263	10	16	12	8
Asd – Ass	232	5	14	5	12
Amr – Asd	218	33	13	34	4
Zd – Ass	209	6	12	6	10
Hn - Asd	209	34	12	33	4
Wm – Asd	83	15	5	22	4
Hdr – Amr	47	40	3	35	2
Ekz – Ass	27	71	2	53	4
Asd –Utg	26	26	2	29	4
Ass – Wm	26	14	2	16	4
Hn – Pmo	18	12	1	11	2
Amrn - Hwd	18	5	1	5	2
Hdrz – Ass	18	61	1	66	2
Ass – Utg	17	16	1	24	4
Hn - Ekz	17	35	1	23	2

In general, there is no convincing pattern apparent in travel time changes shown in table 6.5. Rail DRT is quicker in 7 occasions, while the 2016 time table offered faster service on 5 OD-pairs. Using the data over all OD-pairs in appendix J provides a different view. Overall, the product of passenger demand and travel time is 13,775 minutes smaller in the rail DRT system compared to the 2016 time table. This is an average of 2.0 minutes per passenger. In other words, there may be positive and negative changes in travel time between both systems on an OD-level, but the overall travel time is shortest in rail DRT.

Table 6.5 shows that travel time from Enkhuizen (Ekz) to Amsterdam Sloterdijk (Ass) is significantly higher in the rail DRT system. At first, one may pose the question if there is a general pattern of long-distance OD-pairs having a longer travel time in a rail DRT system, for example because of the delays experienced at numerous intermediate stations. Therefore, the top-5 longest distance OD-pairs are examined separately in table 6.6 and appendix J is studied for any notable patterns.

Table 6.6 shows that the travel time in rail DRT on long-distance routes is, in general, somewhat shorter than in the 2016 time table, except for the relation Bovenkarspel-Grootebroek – Amsterdam Centraal and Enkhuizen – Amsterdam Sloterdijk. The underlying cause is that a part of the vehicle flow operating between these OD-pairs is routed via the higher capacity route from Zaandam to Hoorn via Alkmaar, instead of the shortest option via Purmerend. Apparently, this particular routing has been found beneficial by the model to attain a system optimum. In general, from inspection of appendix J, there appears to be a slight tendency to have better travel time in the DRT system on medium-short routes. On longer routes, there can be large difference in positive and negative sense on an OD-base, although the general picture is that there is not one system which performs significantly better. Over the top 10 longest routes, the rail DRT is 4.2 seconds slower on average compared to the 2016 time table in the conventional system.

Table 6.6: Comparison of travel time in minutes on the five longest distance OD-pairs of the case study area in the morning rush hour. Shortest travel time per OD-pair is underlined.

	Distance	Rail DRT		2016 Time table	
OD-pair	**[km]**	**Travel time [min]**	**Hourly frequency**	**Travel time [min]**	**Hourly frequency**
Hdr – Asd	82	<u>64</u>	1	76	2
Hdrz – Ass	75	<u>61</u>	1	66	2
Ekz – Asd	62	<u>57</u>	2	61	4
Sgn – Asd	62	<u>42</u>	2	59	2
Bkg – Asd	59	61	3	<u>52</u>	4

Earlier, it was noted that passengers from Enkhuizen to Amsterdam Sloterdijk may experience an increased travel time, because part of the vehicle flow on this OD-pair is allocated a longer route. Generally speaking, the case study network allows for two routes to be taken between origins and destinations on either end of the network. One route option is via Alkmaar (the western branch) and the other runs through Purmerend (the eastern branch). Depending on the specific OD-pair, either one of the branches is quickest. Table 6.7 provides an overview of which OD-pairs have their vehicle flow routed via both route options, including free flow travel time and share of flow per route.

Generally speaking, the major part of all vehicle flow on an OD-pair will take the shortest route. Indeed, when the difference in travel time between the two options becomes smaller, the distribution of flow over the routes starts to level. The biggest share of flow not to take the shortest route is 34% between Amsterdam Centraal and Heerhugowaard. In this case, the smaller number of stations on the alternative route, and correspondingly a reduced chance of delay at intermediate stations, is the most likely explanation for the relatively high share of vehicles.

Table 6.7: Overview of vehicle flow routed via either one of two route options.

	via Alkmaar		via Purmerend	
OD-pair	**Free flow travel time [min.]**	**Share of flow**	**Free flow travel time [min.]**	**Share of flow**
Asd - Hn	39	9%	27	91%
Asd - Hnk	40	18%	28	82%
Asd - Hwd	29	66%	37	34%
Ass - Hnk	38	17%	25	83%
Ass - Hwd	26	68%	34	32%
Bkg - Asd	47	16%	35	84%
Bkg - Ass	44	18%	33	82%
Ekz - Asd	49	19%	37	81%
Ekz - Ass	46	19%	35	81%
Hdr - Asd	49	67%	57	33%
Hdrz - Ass	45	67%	53	33%
Hks - Asd	45	15%	33	85%
Hks - Ass	42	15%	30	85%
Hn - Asd	38	5%	27	95%
Hn - Ass	36	5%	24	95%
Hnk - Asd	40	8%	28	92%
Hnk - Ass	37	8%	25	92%
Hwd - Asd	28	81%	37	19%
Hwd - Ass	26	81%	34	19%
Hwd - Zd	21	76%	30	24%
Sgn - Asd	37	72%	45	28%
Sgn - Ass	34	73%	42	27%

6.2.2 *Sensitivity to changes in minimum hourly service frequency threshold*

Table 6.8 holds the case study results of the two scenarios on minimum hourly service frequency threshold. Figure 6.7 displays the corresponding radar graph representation.

Table 6.8 shows that the percentage of unserved demand decreases from 4% to 0% when setting the minimum service frequency to one departure per ten hours. Still, in this scenario 2% of all passengers require a transfer, compared to 13% in the first scenario with at least one departure per hour. This implies that rail DRT in the current system definition cannot serve all passengers free of transfer.

The results in table 6.8 indicate that in order to serve the last 4% of all passenger demand, the fleet size increases by over 19%. Fleet size in itself is not a cost component in the model. Therefore, the system is not penalized for having a larger fleet. Nevertheless, the results raise the (political and social) question whether the operator must serve all demand or if it is justifiable to suspend service to low yielding stations.

Table 6.8: Case study results of the scenarios with different minimum hourly service frequency. Results are expressed in terms of objective function components and related parameters.

Parameter	**Units**	**≥1 per hour**	**≥0.1 per hour**
Arc costs	*[€1000]*	17.94	20.61
Node costs	*[€1000]*	14.61	17.08
Operational costs	*[€1000]*	5.07	6.16
Passenger costs	*[€1000]*	24.32	29.24
Fleet size	*[vehicles]*	191	230
Offered seat kilometres	*[1000 km]*	253.6	308.0
Passenger kilometres	*[1000 km]*	177.5	215.6
Unserved demand	*[-]*	4%	0
Share of transfers	*[-]*	13%	2%
Service effectiveness	*[Paxkm/paxhrs]*	73	74
Cost effectiveness	*[€ / paxkm]*	0.35	0.34

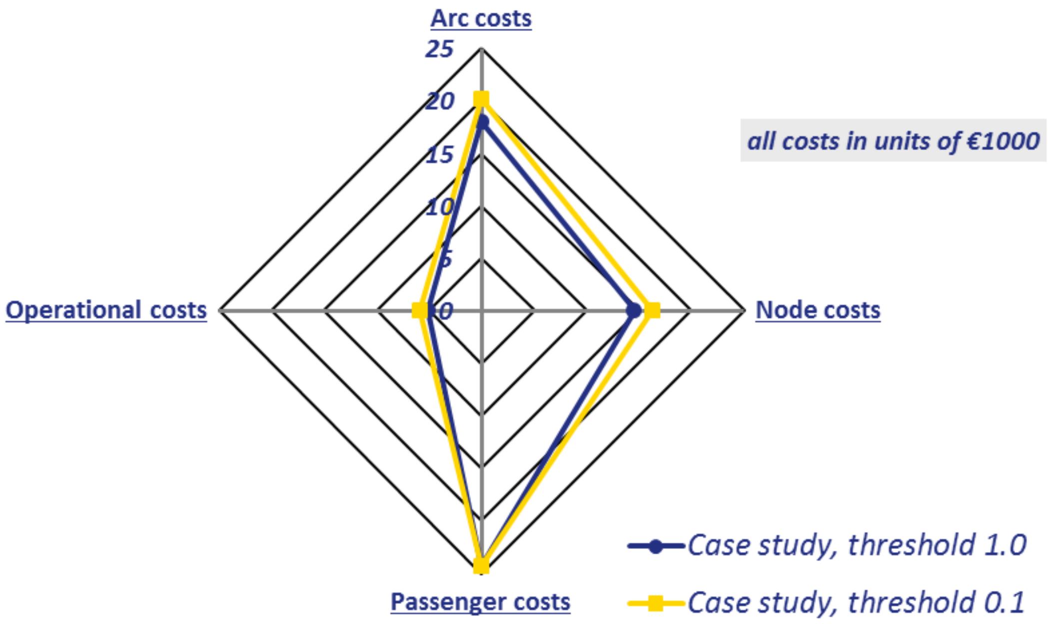


Figure 6.7: Radar graph representation of the case study results.

When decreasing the service threshold from 1.0 to 0.1 departures per hour, new services are provided on long-distance OD-pairs in particular. This is visible from the increase in passenger kilometres (up by 21%) compared to the relatively smaller increase in passenger numbers (13%). The additional traffic induced by long-distance travellers would lead to a major increase in total travel time and passenger costs if infrastructure capacity would not be increased. Indeed, the infrastructure capacity on arcs is expanded over the entire network, although the effects are hard to see in practice due to rounding effects.

Cost effectiveness and service effectiveness are constant among the scenarios. In other words, despite the increase in offered seat kilometres (more vehicles running through the system), the average operational speed does not decrease. This can be examined from table 6.9, which shows the travel time on the five busiest routes in the network. A comparison of total travel time on the network, or an average travel time, would be unfair, because the scenario with a lower minimum service frequency serves more passengers and carries them over a longer distance.

Table 6.9: Comparison of travel time in minutes on the five busiest OD-pairs of the case study area in the scenarios with different service frequency thresholds.

		Travel time in minutes		
OD-pair	**Demand [pax/hr]**	**Service frequency ≥ 1**	**Service frequency ≥ 0.1**	**2016 time table**
Zd – Asd	263	10	10	12
Asd – Ass	232	5	5	5
Amr – Asd	218	33	33	34
Zd – Ass	209	6	7	6
Hn - Asd	209	35	36	33

6.2.3 *Sensitivity to changes in track capacity*

Figures 6.8, 6.9 and table 6.10 contain the results of the sensitivity analysis into track capacity in the case study. Figure 6.8 indicates that the arc costs increase exponentially with decreasing track capacity. Meanwhile, passenger hours appear to increase linearly at first, while the growth tends towards exponential when track capacity falls below 90 vehicles per hour. These results show that, given the selected passenger value of time, the model first tries to limit growth in passenger travel time at the cost of increased infrastructure costs. Only once the arc capacity costs increase sharply, will the arc costs be traded off partly against passenger travel time costs. This is supported by the service effectiveness data in table 6.10, which show that average operational speed is not affected significantly by decreasing track capacity until the aforementioned area around 90 vehicles per hour.

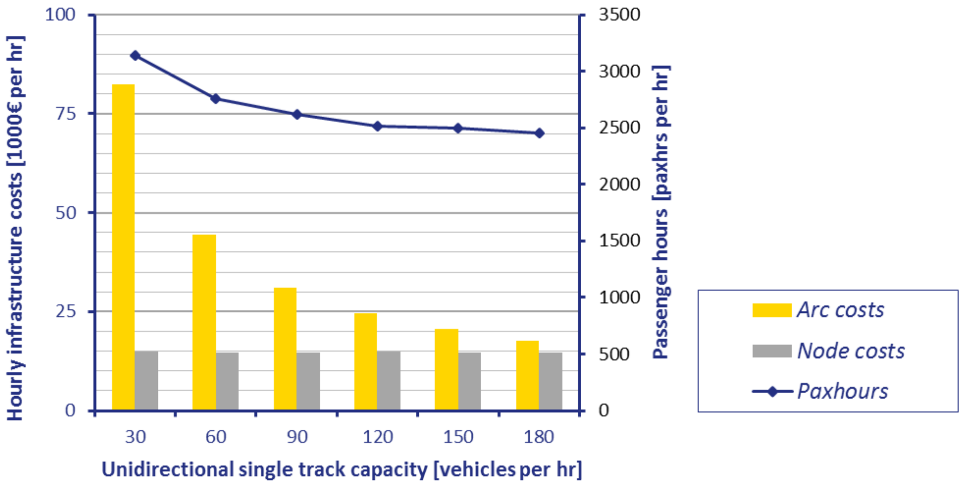


Figure 6.8: Sensitivity of infrastructure costs and passenger hours to changes in track capacity in the case study.

Table 6.10: Case study results of the scenarios with different track capacity. Results are expressed in terms of objective function components and related parameters.

		Single track capacity in vehicles per hour					
Parameter	**Units**	**30**	**60**	**90**	**120**	**150**	**180**
Arc costs	*[€1000]*	82.48	44.32	31.10	24.48	20.52	17.94
Node costs	*[€1000]*	14.86	14.73	14.75	14.88	14.75	14.61
Operational costs	*[€1000]*	5.06	5.08	5.09	5.09	5.12	5.07
Passenger costs	*[€1000]*	31.42	27.59	26.20	25.14	24.95	24.32
Fleet size	*[vehicles]*	247	217	206	197	196	191
Offered seat kilometres	*[1000 km]*	253.1	254.0	254.3	254.6	255.9	253.6
Passenger kilometres	*[1000 km]*	177.2	177.8	178.0	178.2	179.1	177.5
Unserved demand	*[-]*	4%	4%	4%	4%	4%	4%
Share of transfers	*[-]*	13%	13%	13%	13%	13%	13%
Service effectiveness	*[Paxkm/paxhrs]*	56	64	68	71	72	73
Cost effectiveness	*[€ / paxkm]*	0.76	0.52	0.43	0.39	0.36	0.35
Average travel time change (in-vehicle time) compared to the 2016 time table	*[minutes per passenger]*	+4.2	+0.9	-0.4	-1.3	-1.5	-2.0

Figure 6.9 shows that the amount of seat kilometres offered by the rail DRT system is hardly affected by the changes in track capacity. Vehicle flow rerouting does not occur as a result of changing track capacity. This can be explained from the fact that all arcs in the network are equally affected. A different result could be possible if parts of the network were allowed a higher or lower track capacity, for example because of larger minimum headways in tunnels.

The average travel time change in comparison to the 2016 time table in the conventional system shows that the rail DRT system offers lower in-vehicle time when single track capacity is higher than 90 vehicles per hour in the case study area. However, note that the purpose of this case study is not to provide an advisory track capacity. For that purpose, additional data would be required. For example, if the development and implementation of a high track capacity is much more expensive than a lower capacity, the optimal track capacity will be at a different location than in case the correlation between track capacity and development or implementation costs does not exists.

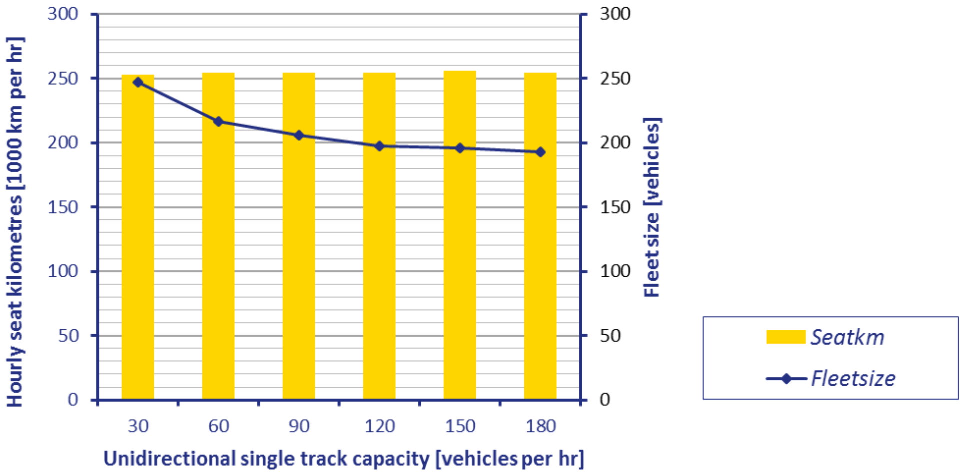


Figure 6.9: Sensitivity of seat kilometres and fleet size to changes in track capacity in the case study.

6.2.4 *Sensitivity to changes in vehicle size*

In contrast to the proposal to study a scenario with 12, 24, 48 and 96 seats per vehicle, the 96 seat scenario is not included. It would result in 40% unserved demand, which is considered unwanted. Results of the remaining scenarios are presented in table 6.11. Comparison of results requires additional care, because the smaller vehicle scenario has a lower share of unserved demand. Therefore, it serves more customers, in particular long-distance passengers. This leads to unfair comparisons of average travel time or fleet size. Therefore, the sensitivity analysis of vehicle size will focus on a different aspect of the results.

Table 6.11: Case study results of the scenarios with different minimum vehicle size. Results are expressed in terms of objective function components and related parameters.

Parameter	Units	12 seats	24 seats	48 seats
Arc costs	*[€1000]*	33.68	17.94	9.99
Node costs	*[€1000]*	24.13	14.61	9.90
Operational costs	*[€1000]*	5.59	5.07	4.24
Passenger costs	*[€1000]*	28.61	24.32	20.19
Fleet size	*[vehicles]*	450	191	79
Offered seat kilometres	*[1000 km]*	279.4	253.6	212.2
Passenger kilometres	*[1000 km]*	195.6	177.5	148.5
Unserved demand	*[-]*	1%	4%	13%
Share of transfers	*[-]*	8%	13%	17%
Service effectiveness	*[Paxkm/paxhrs]*	68	73	74
Cost effectiveness	*[€ / paxkm]*	0.47	0.35	0.30

Figure 6.10 and table 6.11 learn that the choice of vehicle size has consequences for cost effectiveness and, depending on the nature of the demand distribution, for operational speed. Note that the share of unserved demand increases sharply with growing vehicle capacity. There is no explicit relation between these two elements. It simply depends on the demand size per OD-pair. Therefore, it is worthwhile to examine a histogram of the demand size per OD-pair, shown in figure 6.10. The majority of all OD-pairs in the case study have less than 10 passengers per hour. However, demand on most of those OD-pairs is so low, that even if the vehicle size increases beyond 10 passengers (and hence the low yield OD-pairs are no longer served directly), over 98% of all demand still has a service (direct or via a transfer). It is up to the operator to determine an acceptable minimum share of served demand. In the case study, this question is most prominent for Zaandam Kogerveld, which would not be served in the current base case definition.

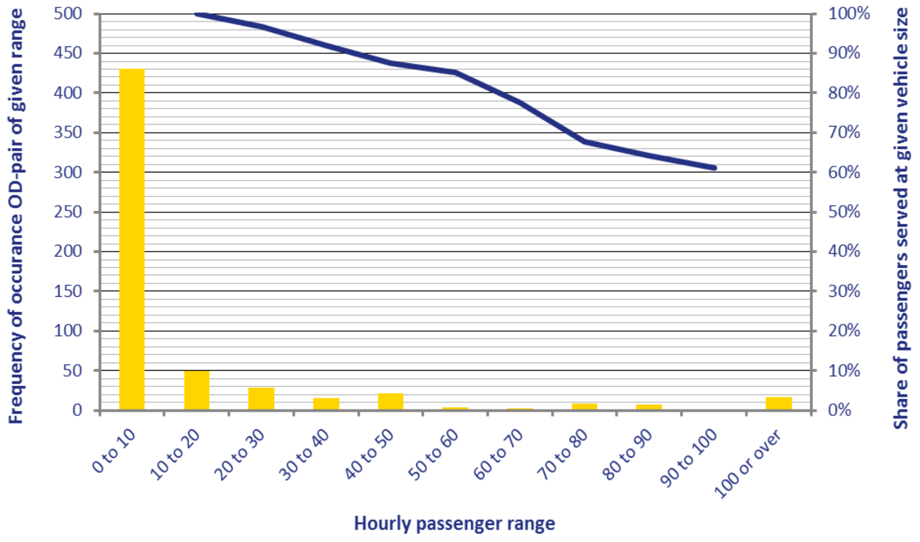


Figure 6.10: Histogram of passenger demand per OD-pair shown by the yellow bars. The blue line represents the share of passengers which are served if the vehicle size is chosen within the given range on the horizontal axis (assuming a minimum service frequency of 1.0 departures per hour).

7. Conclusions and recommendations

Applying demand responsive transport as a substitute for current heavy rail services has not been considered in literature or practice before. This thesis is a first step into the relatively unknown area of rail DRT. The research aims at gaining insight into the relation between operational performance and network characteristics. The following chapter presents the conclusions and recommendations. First, section 7.1 addresses all key findings and contributions. Section 7.2 elaborates with a discussion of stakeholder interests. Finally, section 7.3 holds suggestions for future research.

7.1 Key findings and contributions

One main research question and five corresponding sub questions have been defined to govern this thesis. Generally speaking, the research questions can be categorized into the following three topics: scope and outline; research methodology; and results and analysis. Each of those is discussed next.

7.1.1 Scope and outline

Literature study showed that only a handful of researches exist into public transport concepts which could be considered rail DRT. Most pioneering work has been done by Anderson (1998) and more recently an exploratory study was performed by Haverkamp & Maat (2015). The absence of relevant literature is attributed to an observed phenomenon given the name 'rail DRT paradox'. Conventional (road) DRT systems and heavy rail services are at opposite sides of the transport spectrum in terms of ridership and coverage. Nevertheless, the fact that rail DRT has never been implemented before, is considered a stimulus to study and explore this field rather than an inhibitory factor, in particular with new road and rail technology emerging on the market in recent years.

In addition to the rail DRT paradox, four barriers have been identified which add uncertainty to a successful development and implementation of rail DRT:

- Innovation is required to develop the existing rail technology into a properly functioning DRT system. Currently, all actors involved show little interest in moving forward in this area, because they are comfortable in the current market. Recent developments in the car industry on automated driving, could change this attitude.
- Implementing rail DRT requires a full system change. Various experts in the field consider a gradual transition to be impossible or at least highly unlikely due to the complexity.
- Rail DRT is associated with high investment costs.
- Current developments and visions about the future of rail transport counteract some of the rail DRT system requirements. To prevent unnecessary investments and to ensure that rail DRT can still be implemented successfully in future, the concept of rail DRT should be considered and included in visions and reports today.

The rail DRT paradox emphasises the importance of a clear answer to the following research question, to ensure a realistic project scope: "What are the (technical) system characteristics of rail bound DRT considered in this research?" Rail DRT is considered a full replacement of scheduled heavy rail. Vehicles move around a rail network autonomously, based on passenger requests. Every vehicle may have its own route. Vehicles are sized according to the operator's preference, but they are considerably smaller than current trains, having 100 seats at most. Larger vehicles will result in an increased share of unserved demand as a consequence of transforming the passenger OD-matrix into a service frequency table under the limitation of a minimum service frequency threshold and the assumption of a fixed load factor.

Passenger demand is assumed to be known on forehand and it is uniform over one hour. There is no service guarantee. Passengers are assigned to vehicles such that transfer free travel is offered to as many customers as possible. However, some low yielding OD-pairs may not be served, depending on the operator's preferred minimum service frequency threshold. There is a specific risk of not serving long-distance passengers, because their numbers are often small. This is particularly relevant when benchmarking the DRT system to the conventional system. In some cases, a station may not even be served at all. In the case study performed in this research, one station was not served, because passenger demand on all incoming and outgoing routes did not meet the minimum size imposed by the service frequency threshold.

The system is run by a single operator. Hence, there is a system optimal case. User equilibrium would be the best option when multiple operators exist. However, that case was outside the scope of this research and including it would require a redefinition of the research model's objective function. Network robustness, stability and resilience have not been studied. Freight transportation is omitted.

7.1.2 Research methodology

Considering the rail DRT system as a variant of a network flow problem was preferred over dial-a-ride methodology and rule-based modelling. The other options were disregarded based on disadvantages such as pseudo-accuracy – an adverse effect identified in earlier study by Haverkamp & Maat (2015) - and incapability of handling large scale network – a typical point of concern in vehicle routing problems. The network flow problem assesses the rail DRT system at a strategic level, which is in accordance to the project scope. These decisions and argumentation about the model answer the following sub question: "Which model is preferred such as to attain sufficient accuracy and limited complexity in solving the optimization problem?"

The network flow problem has been redefined to represent a rail DRT system. The decision variables are arc capacity, node capacity and share of vehicle flow routed via each available route option between all OD-pairs. The objective function aims to minimize the cumulative value of infrastructure capacity costs (nodes and arcs), passenger travel time costs and operational costs. These elements are in accordance to common practice in rail cost-benefit analyses. It does require a conversion into monetary units of all major output.

A logistic function governs the relation between attained speed and density on arcs. Its parameters have been set by comparison to autonomously driving car theory and by considering specific UIC advices. Waiting time at nodes is determined from queuing theory. This approach was favoured over simpler functions, because queuing theory has the ability to handle the highly heterogeneous service characteristics of rail DRT. The most important underlying principle is the assumption of Poisson arrivals of vehicles into each node. The validity of this assumption may be questioned when there are multiple sequential low capacity nodes. This assumption can only be verified by empirical data or microscopic simulation. It is a suggestion for further study.

The model has been implemented in Matlab. It is capable of solving networks up to at least 30 nodes, 60 arcs and 35,000 requests per hour. Running time increases sharply when the network of interest is highly symmetric or when it offers large numbers of route options per OD-pair. In any case, the general input to the model is a network composed of a set of node and arcs, each having an initial capacity and, for arcs, a free speed as well. Furthermore, vehicle size, average load factor, dwell time characteristics, value of time, service frequency threshold, unit infrastructure costs, unit operational costs and unit track capacity are input variables to the model. Output is the assigned infrastructure capacity per arc and node, the fleet size, the share of vehicle flow per route option per OD-pair and the value of each of the four cost components in the objective function.

Input and output to the model have been selected such that the relations in the main research question can be studied adequately. Note that level of service is included in both the input (average load factor, maximum detour, minimum frequency) and output (in-vehicle time). One could pose the question if a load factor (percentage of occupied seats) in excess of 1.0 is allowed. In current train networks, passengers need to stand upright during rush hour on some high demand routes. When not allowing passengers to stand in a rail DRT system, this might have significant implications for the total system costs. This is a suggestion for further study. In any case, the aforementioned decisions and definition about the rail DRT model provided an answer to the following sub questions: “Which input, output, decision variables, objective and constraints govern the rail DRT model?” and “How, in terms of units and level of detail, can the performance indicators best be expressed?”

7.1.3 Results and analysis

The main conclusions are obtained from the results of several numerical experiments and a case study. The scenarios considered in the research have been selected such that the main question can be answered: “How do network structure and passenger demand distribution relate to station platform capacity, track capacity, fleet size, level of service and offered seat kilometres in rail DRT systems as a full substitute of scheduled heavy rail?” In addition to answering this main question, the results are used in respect to the following sub-question: “Which system characteristics are factors of influence affecting the relations mentioned in the main research question?”

First, concern the network structure in general. Although certain network structures appeared to have better ability of reducing the objective function value at specific demand distributions, the overall pattern is that a network will offer lowest costs per passenger kilometre when the network is most dense and has best connectivity in the area of highest demand. In practical terms, this implies that stations should be higher in number and closer together in areas of high demand, such as urban regions. In low demand zones, such as rural areas, the number of stations should be more conservative. Else, there is a risk of a station not being served at all. In the case study, this happened at Zaandam Kogerveld. Naturally, the minimum service frequency can be lowered to force the rail DRT system to serve all OD-pairs and all stations, regardless of their demand size. However, a relatively large fleet is needed to serve only a small part of the customers. The case study indicated up to 50% more vehicles were required just to serve 10% of the customers. Although these passengers travelled longer distances than average, explaining part of the substantial fleet growth, the phenomenon in itself raises the question whether or not the operator must serve all demand.

It can be stated that the sensitivity of the overall results to changes in unit operational costs are negligible within the range of unit operational cost values suggested by NS. To be more exact, while the value of operational costs rises with increasing seat kilometre price, all decision variables in the model remain untouched. Only once the unit operational costs exceed €0.30 per seat kilometre, will the decision variables be affected. Choices on available infrastructure capacity and vehicle flow routing can be made regardless of unit operational costs. This is an important conclusion with respect to the development of rail DRT vehicles. Even in the unfortunate case when rail DRT vehicles are more expensive than anticipated, the strategic choices on available infrastructure need not be revised.

A side note must be made regarding unit operational costs. They are expressed in units of price per distance. This is time-independent, which may not be accurate in case of major congestion on the network. Also, the computation of total seat kilometre count is based on service kilometres only. Deadheading is not included, while it is estimated to be 20% of all mileage. Therefore, an update on the definition of seat kilometre count is suggested for further research. Nevertheless, the earlier conclusion about insensitivity of strategic decisions to unit operational costs remains, given the extreme value at which the unit operational costs become influential.

Another interesting conclusion is that arc capacity is more critical to system performance than node capacity. This is opposite to the current rail network in which stations often are the bottleneck. Node capacity in the case study is very similar to the current system. However, infrastructure utilization is higher, in the order of 70% to 85%, compared to approximately 65% today. Moreover, arc costs are very sensitive to the vehicle characteristics of minimum headway and the speed-density relation. Trading-off arc costs against passenger costs (longer travel time) is possible. Another option to limit arc costs is to increase vehicle size. It comes at price of reduced service frequency. One option would be to tailor vehicle size to the demand level (introduction of a heterogeneous fleet) to prevent high levels of unsatisfied demand. This is suggested for further research. Ultimately it must be noted that arc costs are affected by rounding effects in practise. The rail DRT model considered continuous variables, while railway tracks exists in integer numbers only.

Routing of flow over the available route options is a decision variable. Despite being a fundamental element in the model formulation, rerouting is very rare. Only in extreme cases a minor part of the vehicle flow does not take the shortest route. In networks with a higher availability of equal length route options, even distribution of flow is somewhat more common. Still, a focus on tailoring infrastructure capacity to fit with a free flow vehicle distribution, is considered more beneficial for the objective function than to include the complex rerouting option.

Ultimately it is concluded that above all, the numerical experiments with fictional networks were particularly useful to explore the capabilities and restrictions of the rail DRT model, while they were less suited to find specific relations between input and output variables. The latter can better be sought through case study modelling instead, because there is a greater feeling and intuition with practise. One must always be careful though, that the very nature of rail DRT may have profound influences on known data such as demand patterns and passenger flows. This could, however, be topic of an entire thesis on its own.

7.2 Stakeholder interests

The key findings in section 7.1 identified a strong interaction between the system definition, model formulation and final results. Therefore, for the rail DRT operator it is important to state clearly what the exact DRT system definition will be, including choices on service type. For example, in this thesis, the choice for a non-stop, direct service with a minimum frequency imposed that some OD-pairs or even entire stations were not served at all.

Immediately, this statement raises a new question, which was already touched upon briefly in the precursory section: “Does the operator need to serve all demand?” In fact, this partly is a political discussion with consequences for society. The issue is particularly critical when replacing an existing rail network by DRT. In this case, passengers are used to the current station locations and possible closure may be cause of protest or agitation against the new technology.

It is highly recommended to study the possible resistance of the public and develop an implementation strategy. Furthermore, the operator must consider resistance of staff against rail DRT, in particular the aspect of autonomous vehicles making drivers obsolete.

Finally, rail DRT offers new possibilities for concessions and tendering. Currently, the entire main line railway network is operated by one single operator: NS. However, in rail DRT with smaller vehicles, shorter headways, higher frequency and less network coherence (more point-to-point transport), there may be little objections against multiple operators running their vehicles simultaneously like a taxi service.

7.3 Suggestions for future research

A variety of suggestions for future research have already been proposed earlier in the report. All of them are presented concisely hereafter. The suggestions are grouped into two categories: updates to the existing rail DRT model and other proposals.

7.3.1 Updates to the existing rail DRT model

A point of concern raised during assessment of results is the average load factor of just 70% used throughout this thesis. The operator may require to have a seat for everyone or accept that people stand upright during some periods of day. Therefore, it is suggested to run the rail DRT model with load factors exceeding unity. This is expected to have consequences for the required infrastructure capacity, because a change in load factor is equivalent to a change in vehicle size, since it affects the service frequency per OD-pair.

An option for further optimization is to tailor vehicle size to the demand level per OD-pair. In this way, a heterogeneous fleet is introduced with the aim to prevent high levels of unsatisfied demand and move towards a more uniform service frequency among the network. However, this suggestion cannot be implemented without considering one of its implications. In a homogenous fleet, all vehicles can be deployed on all routes, while in the heterogeneous alternative the options for efficient vehicle circulation are limited. Therefore, the estimation of fleet size needs reconsideration.

Queuing theory is a fundamental element in the rail DRT model. It is based on the assumption of Poisson distributed vehicle arrivals at nodes. It was identified that this assumption may not be valid in case of multiple sequential low capacity stations. Therefore, it is suggested to explore if another distribution would be more accurate a representation of vehicle arrivals at these stations. The corresponding implications on the queuing theory equations should naturally be considered as well.

Finally, an updated definition of the seat kilometre count is suggested for future research. In this way, the aspect of deadheading, being up to 20% of all mileage, is included in the operational cost component. Implementing this suggestion requires a better insight in vehicle circulation. It is unclear whether or not the strategic, macroscopic nature of the model allows for generation of such detailed information. Therefore, this may be one of the most challenging suggestions for future research.

7.3.2 Other proposals

The rail DRT system in this thesis considered passenger transport only. In practise, this is impossible, given that rail is an important mode for freight transport. Studying mixed traffic operation will therefore be of particular interest for practical applications and case studies.

Frequently, this thesis refers to the exploratory study by Haverkamp & Maat (2015). Among others, there is one major difference between the aforementioned research and this thesis. It is the very definition of rail DRT. The 2015 study considered a system of vehicles which had to accommodate real time passenger requests. Stochasticity was a major aspect in its microscopic, operational model. This thesis considers demand as fully known on forehand and no stochasticity is involved at all. On a more fundamental level, this raises the question: “Is DRT merely a means to tailor the supply to the expected demand or should DRT be a full real time responsive system?” The answer to this question affects the entire setup and viewpoint of the research. A suggestion is to explore the possibilities and effects in greater detail.

In the case study, this thesis applied current passenger data straight to the rail DRT model. It was noted that rail DRT could have profound influences on known data such as demand patterns and passenger flows. Studying the effects of rail DRT on passenger demand distribution, station attractiveness and travel behaviour is a suggestion for an entire study on its own.

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Appendix A – Ridership and travel distances of various public transport modes in The Netherlands and foreign DRT systems

The following public transport lines and DRT systems have been included in the figure 2.1. Their average speed has mostly been retrieved from time table analysis. Ridership numbers have been collected from annual reports, governmental papers and tendering documents. A confidentiality agreement has been signed with two agencies regarding the latter. Figures may be shown if they do not hold the explicit numerical values. Therefore, these numbers are not included and fort clarity this policy has been used consistently for all of the systems listed hereafter.

Urban transport

Amsterdam,	Metro 50, 51, 53 and 54. Tram 1, 5, 9, 14 and 26 Bus 21
Rotterdam,	Metro A, B, C, D and E Tram 4, 8, 20 and 25 Parkshuttle (DRT)
The Hague,	Tram 1, 3 and 4
Utrecht,	Bus 12

Rural transport

Noord-Holland,	Bus 81, 170 and 300
West Brabant,	Bus 301
Overijssel,	Bus 76 Regiotaxi NoordWest Overijssel (DRT)
Friesland,	Opstapper (DRT)

Train Service

National level,	High Speed Line South Intercity Amsterdam – Dordrecht Intercity Rotterdam – Groningen
Local level,	Sprinter Rotterdam – Hoek van Holland Sprinter Amersfoort – Ede Wageningen

Foreign systems

Helsinki,	Kutsuplus (DRT)
Boston,	Bridj (DRT)
London,	Heathrow people mover (DRT)
Blacksburg,	Virginia Tech PRT
Bogota,	Bus, BRT network
Tokyo,	Metro, city network
Paris,	Metro, RER line A

Appendix B – Rail DRT operational costs computation

Confidential data

Appendix C – Boarding time observation at Rivium Parkshuttle

Nr.	**Dwell duration [s]**	**Nr.**	**Dwell duration [s]**
1	30	*21*	28
2	24	*22*	21
3	24	*23*	25
4	15	*24*	23
5	19	*25*	18
6	29	*26*	24
7	17	*27*	30
8	24	*28*	29
9	19	*29*	10
10	17	*30*	26
11	25	*31*	20
12	24	*32*	15
13	26	*33*	20
14	12	*34*	17
15	26	*35*	22
16	20	*36*	27
17	22	*37*	18
18	19	*38*	15
19	25	*39*	29
20	10	*30*	21

Average dwell time: 21.6 seconds.

Dwell time is considered the duration between doors opening and the vehicle starting to move again after the doors have closed. Observations have been made during different time moments throughout two office days in December 2016 at stop ‘Rivium 2e Straat’. Recordings were performed using a Casio wristwatch and are rounded to integer seconds.

Appendix D – Rolling stock seat to length ratio

Stock type	**Class**	**Fleet size**	**Length[m]**	**1^{st} class seats**	**2^{nd} class seats**	**Folding seats**	**Seats to length ratio**
ICM III	Single deck	97	80.6	35	163	30	2.8
ICM IV	Single deck	50	107.1	56	211	29	2.8
ICR A	Single deck	76	26.4	59	-	10	2.6
ICR B	Single deck	164	26.4	-	84	12	3.6
DDZ IV	Double deck	30	101.8	67	269	36	3.7
DDZ VI	Double deck	20	153.9	106	439	60	3.9
VIRM IV - series 1 & 3	Double deck	47	108.6	61	322	16	3.7
VIRM IV - series 4	Double deck	51	108.6	62	310	32	3.7
VIRM VI - all series	Double deck	78	162.1	129	432	26	3.6
DM '90	Single deck	22	52.3	12	105	34	2.9
Flirt II	Single deck	6	45.7	12	103	16	2.9
Flirt III	Single deck	33	63.2	32	114	12	2.5
Flirt IV	Single deck	25	80.7	32	170	12	2.7
SGM II	Single deck	30	52.2	24	80	37	2.7
SGM III	Single deck	60	78.7	36	128	58	2.8
SLT IV	Single deck	69	69.4	40	144	32	3.1
SLT VI	Single deck	62	100.5	56	208	58	3.2
DDAR III	Double deck	18	97.3	64	292	29	4.0
DDM IV	Double deck	11	123.2	64	458	18	4.4

$$weighted\ average = \frac{\sum_{fleet\ types} fleet\ size \cdot seats\ to\ length\ ratio}{\sum_{fleet\ types} fleet\ size} \qquad \text{A-1}$$

weighted average over all rolling stock:	3.2 seats per meter
weighted average over single deck rolling stock:	3.0 seats per meter

Appendix E – Demand distribution in the base case scenario

Hourly demand $[pax/hr]$	**OD-pairs**
13	(10,14), (12,16), (14,10), (16,12)
21	(10,13), (10,15), (11,14), (11,16), (12,15), (12,17), (13,10), (13,16), (14,11), (14,17), (15,10), (15,12), (16,11), (16,13), (17,12), (17,14)
23	(2,14), (4,16), (6,10), (8,12), (10,6), (12,8), (14,2), (16,4)
26	(10,12), (10,16), (11,15), (12,10), (12,14), (13,17), (14,12), (14,16), (15,11), (16,10), (16,14), (17,13)
32	(3,14), (3,16), (5,10), (5,16), (7,10), (7,12), (9,12), (9,14), (10,5), (10,7), (12,7), (12,9), (14,3), (14,9), (16,3), (16,5)
43	(2,12), (2,13), (2,15), (2,16), (4,10), (4,14), (4,15), (4,17), (6,11), (6,12), (6,16), (6,17), (8,10), (8,11), (8,13), (8,14), (10,4), (10,8), (11,6), (11,8), (12,2), (12,6), (13,2), (13,8), (14,4), (14,8), (15,2), (15,4), (16,2), (16,6), (17,4), (17,6)
47	(3,15), (5,17), (7,11), (9,13), (11,7), (13,9), (15,3), (17,5)
53	(1,10), (1,12), (1,14), (1,16), (2,6), (4,8), (6,2), (8,4), (10,1), (11,13), (11,17), (12,1), (13,11), (13,15), (14,1), (15,13), (15,17), (16,1), (17,11), (17,15)
84	(2,5), (2,7), (3,6), (3,8), (3,10), (3,12), (3,13), (3,17), (4,7), (4,9), (5,2), (5,8), (5,11), (5,12), (5,14), (5,15), (6,3), (6,9), (7,2), (7,4), (7,13), (7,14), (7,16), (7,17), (8,3), (8,5), (9,4), (9,6), (9,10), (9,11), (9,15), (9,16), (10,3), (10,9), (11,5), (11,9), (12,3), (12,5), (13,3), (13,7), (14,5), (14,7), (15,5), (15,9), (16,7), (16,9), (17,3), (17,7)
106	(1,11), (1,13), (1,15), (1,17), (2,4), (2,8), (3,7), (4,2), (4,6), (5,9), (6,4), (6,8), (7,3), (8,2), (8,6), (9,5), (10,11), (10,17), (11,1), (11,10), (11,12), (12,11), (12,13), (13,1), (13,12), (13,14), (14,13), (14,15), (15,1), (15,14), (15,16), (16,15), (16,17), (17,1), (17,10), (17,16)
211	(1,2), (1,4), (1,6), (1,8), (2,1), (2,10), (2,11), (2,17), (3,5), (3,9), (4,1), (4,11), (4,12), (4,13), (5,3), (5,7), (6,1), (6,13), (6,14), (6,15), (7,5), (7,9), (8,1), (8,15), (8,16), (8,17), (9,3), (9,7), (10,2), (11,2), (11,4), (12,4), (13,4), (13,6), (14,6), (15,6), (15,8), (16,8), (17,2), (17,8)
422	(1,3), (1,5), (1,7), (1,9), (2,3), (2,9), (3,1), (3,2), (3,4), (3,11), (4,3), (4,5), (5,1), (5,4), (5,6), (5,13), (6,5), (6,7), (7,1), (7,6), (7,8), (7,15), (8,7), (8,9), (9,1), (9,2), (9,8), (9,17), (11,3), (13,5), (15,7), (17,9)

Appendix F – Demand distribution in the ‘average closeness scenario’

Hourly demand $[pax/hr]$	OD-pairs
87	(10,12), (10,14), (10,16), (12,10), (14,10), (16,10), (12,14), (12,16), (14,12), (14,16), (16,12), (16,14)
102	(10,11), (10,13), (10,15), (10,17), (11,10), (13,10), (15,10), (17,10), (11,12), (11,14), (11,16), (12,11), (12,13), (12,15), (12,17), (13,12), (13,14), (13,16), (14,11), (14,13), (14,15), (14,17), (15,12), (15,14), (15,16), (16,11), (16,13), (16,15), (16,17), (17,12), (17,14), (17,16)
108	(4,10), (6,10), (8,10), (10,4), (10,6), (10,8), (2,10), (10,2), (4,12), (4,14), (4,16), (6,12), (6,14), (6,16), (8,12), (8,14), (8,16), (12,4), (12,6), (12,8), (14,4), (14,6), (14,8), (16,4), (16,6), (16,8), (2,12), (2,14), (2,16), (12,2), (14,2), (16,2)
110	(3,10), (9,10), (10,3), (10,9), (5,10), (7,10), (10,5), (10,7), (3,12), (3,14), (3,16), (9,12), (9,14), (9,16), (12,3), (12,9), (14,3), (14,9), (16,3), (16,9), (5,12), (5,12), (5,16), (7,12), (7,14), (7,16), (12,5), (12,7), (14,5), (14,7), (16,5), (16,7)
118	(11,13), (11,15), (11,17), (13,11), (13,15), (13,17), (15,11), (15,13), (15,17), (17,11), (17,13), (17,15)
126	(4,11), (4,13), (4,15), (4,17), (6,11), (6,13), (6,15), (6,17), (8,11), (8,13), (8,15), (8,17), (11,4), (11,6), (11,8), (13,4), (13,6), (13,8), (15,4), (15,6), (15,8), (17,4), (17,6), (17,8), (2,11), (2,13), (2,15), (2,17), (11,2), (13,2), (15,2), (17,2)
128	(3,11), (3,13), (3,15), (3,17), (9,11), (9,13), (9,15), (9,17), (11,3), (11,9), (13,3), (13,9), (15,3), (15,9), (17,3), (17,9), (5,11), (5,13), (5,15), (5,17), (7,11), (7,13), (7,15), (7,17), (11,5), (11,7), (13,5), (13,7), (15,5), (15,7), (17,5), (17,7)
135	(4,6), (4,8), (6,4), (6,8), (8,4), (8,6), (2,4), (2,6), (2,8), (4,2), (6,2), (8,2)
137	(3,4), (3,6), (3,8), (4,3), (4,9), (6,3), (6,9), (8,3), (8,9), (9,4), (9,6), (9,8), (4,5), (4,7), (5,4), (5,6), (5,8), (6,5), (6,7), (7,4), (7,6), (7,8), (8,5), (8,7), (2,3), (2,9), (3,2), (9,2), (2,5), (2,7), (5,2), (7,2)
138	(3,9), (9,3), (3,5), (3,7), (5,3), (5,9), (7,3), (7,9), (9,5), (9,7), (5,7), (7,5)
147	(1,10), (10,1), (1,12), (1,14), (1,16), (12,1), (14,1), (16,1)
172	(1,11), (1,13), (1,15), (1,17), (11,1), (13,1), (15,1), (17,1)
184	(1,4), (1,6), (1,8), (4,1), (6,1), (8,1), (1,2), (2,1)
186	(1,3), (1,9), (3,1), (9,1), (1,5), (1,7), (5,1), (7,1)

Appendix G – Interstation distance in The Netherlands

Station pair		Distance [km]	Station pair		Distance [km]	Station pair		Distance [km]
Hdr	Hdrz	2.548	Asdm	Assp	1.320	Vdw	Vdg	2.094
Hdrz	Ana	8.782	Asd	Asdm	3.873	Mss	Vdw	4.399
Ana	Sgn	9.149	Asdm	Asa	2.003	Msw	Mss	1.645
Sgn	Hwd	13.883	Asa	Dvd	2.938	Hld	Msw	8.990
Obd	Hwd	6.077	Rai	Dvd	3.720	Hlds	Hld	0.900
Hn	Obd	10.600	Rai	Asdz	1.450	Dtz	Sdm	8.440
Hnk	Hn	2.317	Shl	Asdz	8.800	Dt	Dtz	1.866
Hks	Hnk	8.072	Asb	Rai	4.972	Rsw	Dt	4.465
Bkg	Hks	3.628	Asb	Asdar	0.765	Gvmw	Rsw	1.704
Bkf	Bkg	1.170	Dvd	Asb	1.500	Gv	Gvmw	2.075
Ekz	Bkf	2.130	Asdar	Dmnz	2.358	Ledn	Ldl	2.841
Hwd	Amrn	5.033	Asb	Dmnz	2.925	Ldl	Apn	12.149
Amrn	Amr	1.840	Dmnz	Wp	7.412	Apn	Bsk	5.831
Amr	Hlo	4.925	Dvd	Dmnz	1.570	Bsk	Bsks	1.022
Hlo	Olv	1.876	Ass*^{2}	Asdl	3.475	Bsks	Wadn	1.373
Olv	Cas	5.020	Ass*^{1}	Asdl	3.388	Wadn	Wad	1.216
Cas	Utg	3.842	Asdl	Shl	8.275	Wad	Gd	8.075
Utg	Hk	3.799	Shl	Hfd	4.695	Gd	Gdg	2.401
Hk	Bv	2.674	Hfdm	Nvp	4.850	Gdg	Wd	13.915
Bv	Drh	4.699	Nvp	Ssh	10.400	Bdg	Wd	10.859
Drh	Sptn	1.093	Ssh	Ledn	6.610	Apn	Bdg	8.121
Sptn	Sptz	1.519	Hlm	Had	4.245	Hfd	Rtd	46.077
Sptz	Bll	1.817	Had	Hil	6.933	Rtd	Rtb	1.947
Bll	Hlm	2.573	Hil	Vh	10.700	Rtb	Rtz	2.373
Hlm	Ovn	2.105	Vh	Ledn	6.820	Rtz	Rtst	1.130
Ovn	Zvt	5.996	Ledn	Dvnk	2.820	Rtst	Rlb	1.732
Utg	Kma	4.740	Dvnk	Vst	2.660	Rlb	Brd	3.143
Kma	Wm	2.692	Vst	Gvm	5.890	Brd	Zwd	7.553
Wm	Kzd	2.530	Gvm	Laa	2.375	Zwd	Ddr	2.092
Kzd	Kbw	1.141	Gvc	Laa	1.615	Ddr	Ddrs	3.452
Kbw	Zd	2.358	Gvc	Gv	1.840	Ddrs	Sdtb	4.145
Zd	Ass*^{1}	7.416	Laa	Gv	1.900	Sdtb	Sdt	2.751
Zd	Ass*^{2}	7.426	Vb	Ypb	3.048	Sdt	Hbzm	2.604
Hn	Pmo	17.859	Ypb	Ztm	5.400	Hbzm	Gnd	1.355
Pmo	Pmr	1.488	Ztm	Ztmo	1.077	Gnd	Bhdv	3.045
Pmr	Pmw	1.601	Ztmo	Gd	15.722	Bhdv	Gr	6.360
Pmw	Zdk	9.165	Nwk	Gd	9.087	Gr	Akl	4.747
Zdk	Zd	2.639	Cps	Nwk	2.657	Akl	Ldm	7.404
Hlms	Hlm	2.592	Rta	Cps	2.105	Ldm	Bsd	7.047
Hwzb	Hlms	5.190	Rtn	Rta	4.968	Bsd	Gdm	6.522
Ass	Hwzb	6.149	Rtd	Rtn	4.808	Rlb	Bd	37.963
Asd	Ass*^{3}	4.625	Sdm	Rtd	3.945	Ddr	Ddzd	2.545
Asd	Ass*^{4}	5.307	Nwl	Sdm	2.275	Ddzd	Zlw	12.057
Dmn	Wp	6.476	Vdo	Nwl	1.910	Zvb	Zlw	7.516
Assp	Dmn	1.545	Vdg	Vdo	1.462	Odb	Zvb	8.036

*^{1}*Via Hemboog;* *^{2}*Via main station;* *^{3}*Direction Haarlem / Zaandam;* *^{4}*Direction Schiphol;*

Station pair		Distance [km]
Rsd	Odb	7.198
Bgn	Rsd	13.656
Rb	Bgn	15.597
Kbd	Rb	3.355
Krg	Kbd	6.643
Bzl	Krg	6.055
Gs	Bzl	5.009
Arn	Gs	15.361
Mdb	Arn	3.538
Vss	Mdb	3.940
Vs	Vss	2.027
Rsd	Etn	12.815
Etn	Bd	9.708
Zlw	Bdpb	10.006
Bdpb	Bd	4.193
Bd	Gz	10.970
Gz	Tbr	4.930
Tbr	Tbu	3.900
Tbu	Tb	2.335
Tb	Ht	22.415
Tb	Ot	8.052
Ot	Btl	8.899
Btl	Bet	9.739
Bet	Ehb	8.065
Ehb	Ehst	1.260
Ehst	Ehv	0.773
Ehv	Gp	6.129
Gp	Hze	4.173
Hze	Mz	9.830
Mz	Wt	8.875
Wt	Rm	24.158
Ehv	Hmbv	9.304
Hmbv	Hmh	1.670
Hmh	Hm	2.155
Hm	Hmbh	2.925
Hmbh	Dn	6.226
Dn	Hrt	17.944
Hrt	Br	10.003
Br	Vl	1.497
Vl	Tg	4.185
Tg	Rv	7.511
Rv	Sm	6.371
Sm	Rm	5.444
Rm	Ec	13.186
Ec	Srn	4.639
Srn	Std	6.589
Std	Lut	3.851
Lut	Bk	4.170
Bk	Bde	7.484
Bde	Mt	5.043
Mt	Mtr	2.677
Mtr	Edn	7.404
Mtn	Mt	1.488
Mes	Mtn	2.780
Sgl	Mes	3.400
Vk	Sgl	2.659
Sog	Vk	3.199
Kmr	Sog	1.770
Vdl	Kmr	3.625
Hrlw	Vdl	2.040
Hrl	Hrlw	1.365
Hrl	Hrlk	1.635
Hrlk	Lg	1.924
Lg	Eghm	2.706
Lg	Egh	2.061
Egh	Cvm	1.912
Cvm	Krd	1.687
Std	Gln	4.145
Gln	Sbk	3.150
Sbk	Sn	1.880
Sn	Nh	2.730
Nh	Hb	3.175
Hb	Hrl	3.180
Vg	Btl	8.226
Ht	Vg	3.935
Zbm	Ht	13.500
Gdm	Zbm	8.620
Ht	Hto	2.500
Hto	Rs	3.960
Rs	Ow	10.640
Ow	O	1.840
O	Rvs	8.260
Rvs	Wc	6.820
Wc	Nmd	4.680
Nmd	Nm	4.831
Nm	Nmh	2.261
Nmh	Mmlh	7.072
Mmlh	Ck	4.902
Ck	Bmr	10.240
Bmr	Vlb	7.050
Vlb	Vry	7.385
Vry	Br	20.623
Wd	Vtn	8.685
Vtn	Utt	2.135
Utt	Utlr	1.665
Utlr	Ut	3.281
Ut	Bnk	7.068
Bnk	Db	4.544
Db	Mrn	7.606
Mrn	Klp	14.209
Klp	Ed	7.076
Ed	Wf	8.750
Wf	Otb	3.385
Otb	Ah	4.361
Mrn	Vndw	12.125
Vndw	Vndc	1.555
Vndc	Rhn	7.240
Ut	Utl	3.900
Utl	Htn	3.735
Htn	Htnc	2.125
Htnc	Cl	8.533
Cl	Gdm	7.787
Gdm	Tpsw	9.020
Tpsw	Tl	2.864
Tl	Ktr	12.073
Ktr	Op	3.743
Op	Hmn	2.519
Hmn	Za	3.430
Za	Est	10.959
Ahz	Est	4.184
Ah	Ahz	6.077
Est	Nml	5.813
Nml	Nm	2.472
Edc	Ed	1.996
Ltn	Edc	5.743
Bnc	Ltn	7.235
Bnn	Bnc	2.504
Hvl	Bnn	9.790
Amf	Hvl	6.877
Brn	Amf	8.741
Hvs	Brn	7.306
Hvs	Hvsp	1.177
Hvsp	Hor	4.325
Hor	Utm	10.978
Uto	Hor	8.844
Ut	Uto	2.947
Uto	Bhv	5.931
Utm	Bhv	7.986
Bhv	Dld	2.781
Dld	Amf	9.173
Dld	Stz	5.138
Stz	St	1.010
St	Sd	1.305
Sd	Brn	3.245
Hvsn	Hvs	1.459
Bsmz	Hvsn	3.090
Ndb	Bsmz	1.678

Station pair		Distance [km]	Station pair		Distance [km]	Station pair		Distance [km]
Wp	Ndb	8.951	Hon	Rsn	7.398	Mrb	Hdb	8.447
Ndb	Ampo	14.843	Dvc	Hon	14.920	Hdb	Gbg	5.566
Asb	Ashd	2.100	Dv	Dvc	3.997	Gbg	Co	7.392
Ashd	Ac	2.725	Zp	Dv	16.002	Co	Dln	3.815
Ac	Bkl	11.875	Nvd	Wdn	8.293	Dln	Na	7.049
Bkl	Wd	12.699	Vem	Zp	4.155	Na	Emnz	3.831
Bkl	Mas	5.185	Kbk	Vem	4.730	Emnz	Emn	5.294
Mas	Utzl	5.195	Apdm	Kbk	6.470	Zl	Mp	27.196
Utzl	Ut	1.952	Apd	Apdm	2.255	Mp	Swk	14.181
Ah	Ahp	1.269	Apd	Apdo	2.650	Swk	Wv	12.280
Ahp	Wtv	4.300	Apdo	Twl	7.013	Wv	Hrij	7.428
Wtv	Dvn	3.780	Hvl	Apd	36.752	Hrij	Hr	3.610
Dvn	Zv	4.658	Twl	Dv	5.110	Hr	Akm	10.667
Zv	Did	4.460	Dv	Ost	9.553	Akm	Gw	4.813
Did	Wl	6.169	Ost	Wh	6.571	Gw	Lw	13.083
Wl	Dtch	3.249	Wh	Zl	13.799	Dei	Lw	4.127
Dtch	Dtc	2.386	Zl	Hno	12.283	Drp	Dei	6.375
Dtc	Gdr	4.921	Hno	Rat	5.669	Fn	Drp	5.949
Gdr	Tbg	1.363	Rat	Nvd	13.580	Hlg	Fn	8.501
Tbg	Vsv	6.895	Zl	Kpn	13.630	Hlgh	Hlg	1.191
Vsv	Atn	8.480	Zl	Dl	12.006	Mg	Lw	9.623
Atn	Ww	12.293	Dl	Omn	10.956	Sknd	Mg	10.704
Ww	Www	0.992	Omn	Mrb	10.792	Sk	Sknd	1.109
Ltv	Www	8.623	Mrb	Gdk	3.866	Ijt	Sk	3.141
Rl	Ltv	12.597	Gdk	Vhp	2.086	Wk	Ijt	12.518
Vd	Rl	9.579	Vhp	Da	1.821	Hnp	Wk	3.626
Zp	Vd	11.681	Da	Vz	4.672	Kmw	Hnp	5.021
Bmn	Zp	7.226	Vz	Aml	6.409	Stv	Kmw	4.209
Dr	Bmn	5.992	Wz	Zl	9.032	Lw	Lwc	3.673
Rh	Dr	6.307	Hde	Wz	9.003	Lwc	Hdg	6.440
Vp	Rh	3.820	Ns	Hde	8.593	Hdg	Vwd	4.063
Ahpr	Vp	2.800	Hd	Ns	12.054	Vwd	Zww	3.360
Ahp	Ahpr	1.849	Eml	Hde	4.484	Zww	Bp	7.479
Zp	Lc	16.905	Pt	Eml	4.812	Bp	Gk	10.888
Lc	Go	13.140	Nkk	Pt	7.459	Gk	Zh	6.626
Go	Ddn	9.571	Avat	Nkk	5.285	Zh	Gn	11.870
Ddn	Hglg	3.629	Amfs	Avat	2.915	Mp	Hgv	19.935
Hglg	Hgl	1.780	Amf	Amfs	3.290	Hgv	Bl	13.944
Hgl	Hglo	1.840	Wp	Ampo	9.518	Bl	Asn	15.571
Hglo	Odz	9.016	Ampo	Almm	3.937	Asn	Hrn	21.941
Hgl	Esd	4.185	Almm	Alm	2.072	Hrn	Gerp	4.208
Esd	Es	4.170	Alm	Almp	1.845	Gerp	Gn	1.374
Es	Ese	4.273	Almp	Almb	3.082	Gn	Gnn	3.915
Ese	Gbr	1.657	Almb	Almo	1.830	Gnn	Swd	6.988
Bn	Hgl	5.295	Almo	Llsz	15.604	Swd	Wsm	4.591
Amri	Bn	7.365	Llsz	Lls	2.470	Wsm	Bf	3.501
Aml	Amri	1.864	Lls	Dron	20.635	Bf	Wfm	4.757
Wdn	Aml	4.693	Dron	Kpnz	13.550	Wfm	Ust	3.191
Rsn	Wdn	7.660	Kpnz	Zl	15.156	Ust	Uhz	4.659

Station pair		Distance [km]
Uhz	Uhm	3.128
Uhm	Rd	2.873
Swd	Bdm	4.191
Bdm	Stm	6.738
Stm	Lp	4.081
Lp	Apg	7.737
Apg	Dzw	3.057
Dzw	Dz	1.129
Gerp	Kw	10.598
Kw	Mth	1.317
Mth	Hgz	1.923
Hgz	Spm	1.607
Spm	Zb	4.915
Zb	Vdm	7.240
Zb	Sda	7.567
Sda	Ws	4.914
Ws	Nsch	12.119

Appendix H – Matlab files and variables description

Table H.1: Definition and description of Matlab files.

File name	Description
arctime.m	This function determines the actual ride time on every arc in the network, taking into account arc capacity and vehicle flow intensity.
constraints.m	This function defines all constraints of the rail DRT problem and computes or reads the corresponding equation values or inequality values.
costs.m	This function computes the value of the objective function and its components.
dijkstra.m	This function uses Dijkstra's algorithm to find the length and path of the shortest (least costs) route between a specified origin and destination in the network.
flowcounter.m	This function determines the vehicle flow at each node in the network, both inbound, through-going and outbound, specified per OD-pair.
init.m	This function creates an initial solution to the rail DRT problem based on freeflow assignment and capacity utilization thresholds.
inputdata.m	This file reads the input data for the rail DRT model from Excel. Sequentially, the input data is processed, prepared for future use and stored in Matlab variables.
main.m	This script is the only one which has to be opened and executed to run the rail DRT problem and all associated files, scripts and functions in Matlab. The main function file prompts the user with an interface to select the input Excel file of preference.
mapper.m	This function extracts the infrastructure capacity vectors c and s from the vector of decision variables. Also, it uses the route choice decision variables to create the vehicle flow matrix per OD-pair and arc.
nodedelay.m	This function computes the average waiting time and density at every node in the network, considering prioritized, non-pre-emptive, M/M/c queuing theory for large stations and non-prioritized queuing theory for small stations. Two vehicle classes are distinguished: 1) non-stop and 2) dwelling. At large stations, class 1 has priority.
optimization.m	This function uses the Matlab optimization tool to minimize the rail DRT problem's objective function, while satisfying all constraints. An initial guess to the solution is provided by the file 'init.m' to start the optimization.
pathfinder.m	This function finds all possible paths between two nodes in the network. Loops are not included. A path which exceeds a predefined travel time limit is excluded.
paxtime.m	This function computes the total amount of passenger hours spend travelling per OD-pair in the rail DRT network during every hour of operation.
paxtoflow.m	This function converts the OD-matrix from units of passengers per hour to units of vehicle departures per hour.
prio.m	This script determines which nodes in the network offer a prioritizing system based on node capacity and the selected threshold above which prioritizing is possible.
props.m	This script determines a variety of rail DRT system properties based on the model's fundamental input parameters.
routesets.m	This function finds all available routes between every OD-pair in the network. The routes are stored in three formats: in arcs, in nodes and in length. All results are stored in a cell array which has a column for the OD-pair's origin node, the destination node and a cell which stores the earlier mentioned properties of all routes between the OD-pair. Lengthy routes are excluded (refer to pathfinder.m).

Table H.2a: Definition and description of Matlab variables.

Variable	Definition and description
A	Arc set matrix holding the origin node and destination node of all available arcs in the network.
alpha	Scaling parameter of the logistic speed-density relation.
arccount	A scalar variable which states the number of arcs in the network.
arclength	A vector holding the length per arc in kilometres.
beta	Shifting parameter of the logistic speed-density relation.
c	A vector holding the decision variable of allocated capacity per arc. Each position represents a node. Capacity is expressed in a continuous variable in units of tracks.
c_init	A vector holding the decision variable of allocated capacity per arc in the initial solution.
c_length	A scalar representing the row number in ‘dvars’ where the arc capacity data ends.
ceq	A vector containing all constraint equalities.
cin	A vector containing all constraint inequalities.
dvars	This vector contains all decision variables of the optimization problem. It can be split into an arc capacity vector ‘c’, a node capacity vector ‘s’ and a route choice vector ‘rc’.
dvars_map	This is a mapping matrix between vector ‘dvars’ and matrix ‘x’.
dvars_route	This variable holds the number of route choice decision variables.
dwell	A scalar value of the average dwell time in hours.
freespeed	A vector holding the free speed per arc in kilometres per hour.
freetime	A vector holding the free flow travel time per arc in hours.
load	A scalar factor of average load factor (share of occupied seats in the vehicle).
maxdetour	A scalar holding the maximum allowed detour factor.
mu_1	Inverse of the average service time of class 1 vehicles (through-going).
mu_2	Inverse of the average service time of class 2 vehicles (dwelling).
nshare	A scalar factor which shows the share of passengers which are not served at all.
nodecount	This is a scalar variable which states the number of nodes in the network.
objval	This scalar holds the objective function value of the rail DRT problem.
odcount	This is a scalar variable which states the number of OD-pairs to be served.
ODflow	Matrix holding the origin node, destination node and demand size for each OD-pair to be served, expressed in vehicles per hour.
ODpax	Matrix holding the origin node, destination node and demand size of every OD-pair prior to any filtering or processing, expressed in passengers per hour.
opscosts	A scalar which holds the operational costs per seat kilometre.
paxhours	This vector holds the total amount of passenger hours spend travelling per OD-pair per hour of operation.
platfcosts	A scalar which states the hourly costs per metre of platform length.
platffix	A scalar which states the vehicle-independent platform length component.
platflength	A scalar which states the length of one platform such that the platform can accommodate the vehicles of the chosen size.

Table H.2b: Definition and description of Matlab variables (continuation of table H.2a).

Variable	Definition and description
priolimit	This scalar holds the minimum number of platforms which a node must have in order to accommodate prioritizing.
r	A vector holding the ride time along each arc in hours.
rc	A vector holding the share of flow per OD-pair which is routed via each route option. Only those OD-pairs which have multiple routes are included.
rc_init	A vector holding the decision variable values of flow share per route option in the initial solution.
rc_length	This scalar represents the number of rows in vector 'dvars' which contain the decision variable of share per route option.
rho	A vector with a position for every node to store the density of all flow into, through and out of the node.
routeops	This vector holds the number of route choices for every OD-pair in the network.
routes	This is a cell array with a row for each OD-pair and columns for the origin and destination node; and a route option column. The last column contains three cells per entry. The first one holds the route options for the OD-pair, expressed in arcs, the second cell holds the route options expressed in nodes and the third cell holds the route lengths of all route options.
s	A vector holding the allocated platform capacity per node.
s_init	A vector holding the decision variable of node platform capacity in the initial solution.
s_length	This scalar represents the row number in 'dvars' where the node capacity data ends.
seats	A scalar value representing the vehicle capacity in seats.
seatspermtr	A scalar value which states the number of seats in a vehicle per metre of vehicle length.
tshare	A scalar factor which shows the share of passengers which are not served directly.
threshold	This scalar value sets the minimum number of hourly departures required for an OD-pair to have direct service.
trackcosts	A scalar which states the hourly unit track costs over one kilometre of single track.
u	A binary vector which states if a node offers overtaking possibilities.
ut_thres	Factor of maximum infrastructure utilization for robust operations.
vot	A scalar value which states the passengers' average value of time.
wait	A matrix holding the average waiting time for class 1 vehicles in column 1 and class 2 vehicles in column 2.
x	A matrix holding the flow per link in the network, sorted by OD-pair. Every row represents a link, while every column represents an OD-pair.
x_in	A matrix containing all flow bound for each node, specified per OD-pair.
x_init	A matrix holding the flow per arc per OD-pair in the initial solution.
x_out	A matrix containing all flow originating from each node, specified per OD-pair.
x_through	A matrix containing all flow through each node, specified per OD-pair.
y	A scalar which sets the theoretical maximum flow per unit of arc capacity.

Appendix I – Case study area comparison

i.1 Triangle Zwolle – Groningen - Leeuwarden

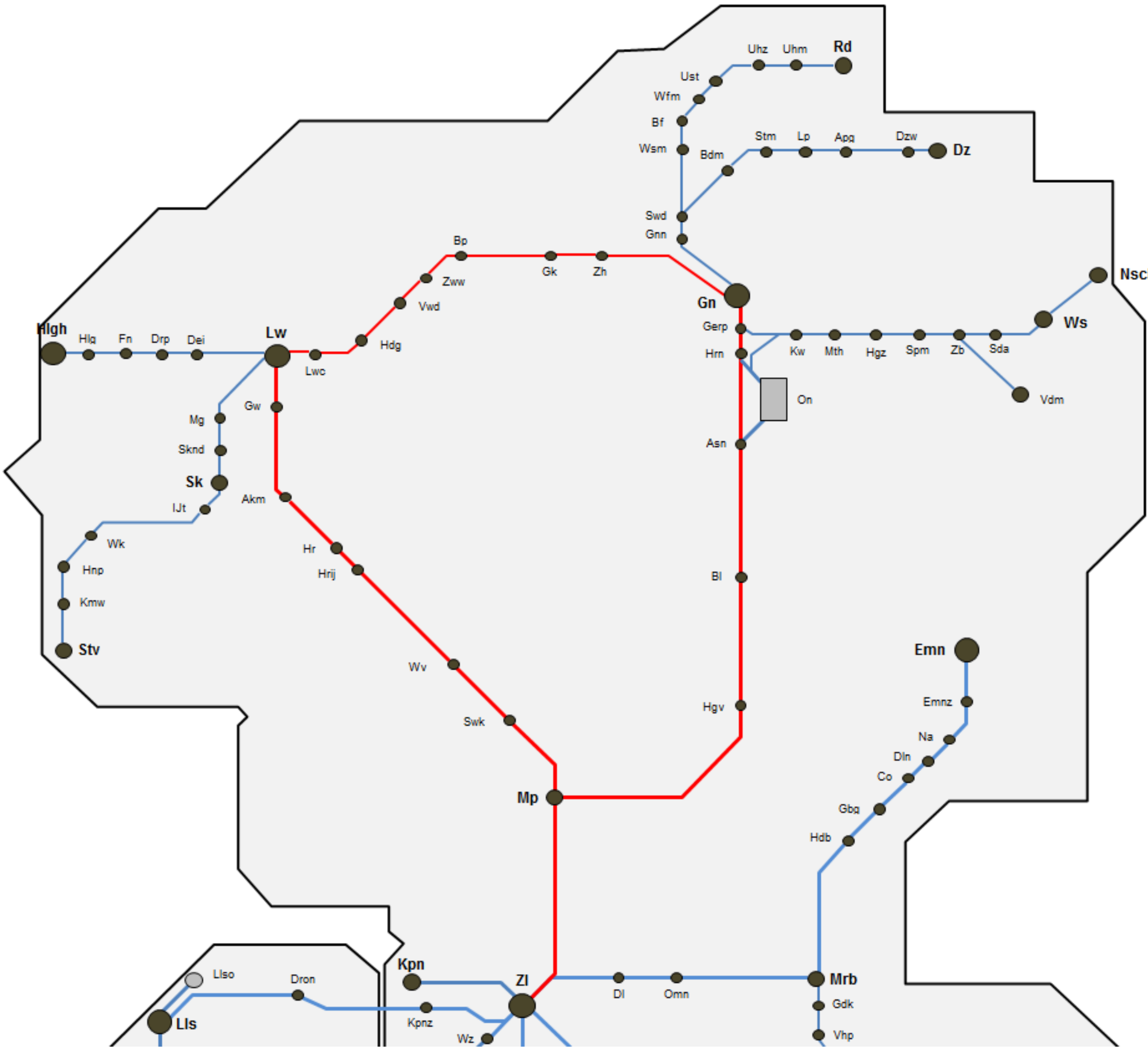

Figure i.1: Triangle Zwolle – Groningen – Leeuwarden indicated by red in the Dutch railway network.

i. 10 Stations are served by NS (Mp, Swk, Wv, Hr, Akm, Gw, Hgv, Bl, Asn & Hrn), 7 stations are served by Arriva (Lwc, Hdg, Vwd, Zww, Bp, Gk, Zh), 4 stations are served by both operators (Zl, Lw, Gn & Gerp) and 1 is open during special events only (Hrij).

ii. The network holds 22 nodes and 44 arcs. There are Confidential data trains during the morning rush hour.

iii. The network allows for rerouting, although detours may be large. The branch from Zwolle to Meppel and vice versa has no alternatives.

iv. The network has only one place of diverging or converging branches: Meppel.

v. Many passengers travel to either one of the three major termini: Zwolle, Leeuwarden and Groningen. There are no assumptions required as to where passengers will transfer to the remainder of the network. On the other hand, current intercity services from Groningen and Leeuwarden to the Randstad will be cut in Zwolle when DRT is implemented to the north of the country. These services are an important segment of busy long distance routes though.

i.2 Area south of Dordrecht, west of Breda

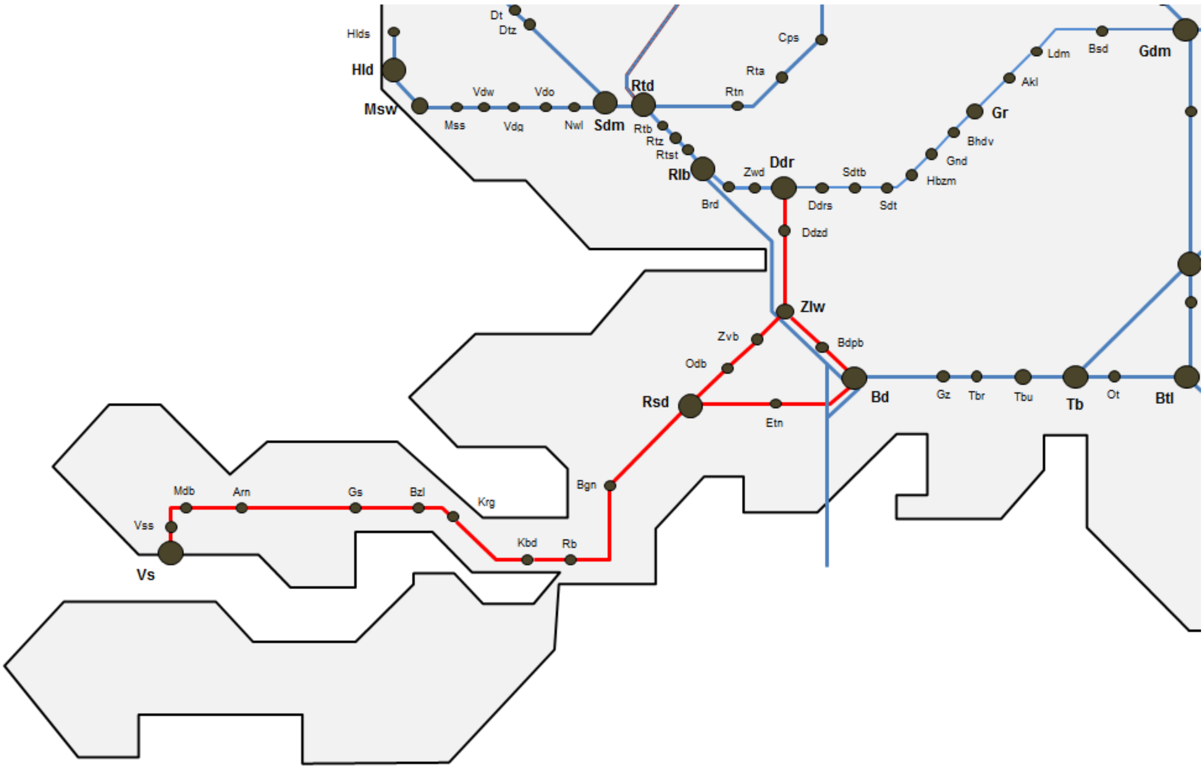

Figure i.2: Area South of Dordrecht, west of Breda indicated by red in the Dutch railway network.

i. 17 Stations are served by NS (Vs, Vss, Mdb, Arn, Gs, Bzl, Krg, Kdb, Rb, Bgn, Odb, Zvb, Zlw, Ddzd, Etn, Bd & Bdpb), 1 station is served by Arriva and NS (Ddr) and 1 is served by NS and NMBS (Rsd). There are no stations or routes within the sub network which are served exclusively by other operators (considering NS and its international daughter company as one joint organisation). NMBS and Arriva only offer services from outside the sub network to the major transfer hubs at the edges of the sub network.

ii. The network holds 19 nodes and 38 arcs. There are Confidential data during the morning rush hour.

iii. The network allows for rerouting. However, this is possible on a small part of the network only. The entire branch into the province of Zeeland has no alternative routes.

iv. The network has two places of diverging or converging branches: Roosendaal and Lage Zwaluwe.

v. The network has many through-going passengers, for example on international routes between Belgium and the Randstad area or from Brabant to the Randstad area. When assuming that all passengers on those routes take the high speed train, these passengers are out of the scope of the sub network. On the other hand, international cargo transport is very prominent in this area, which can be an issue when switching to DRT.

i.3 'Oude Lijn' from Amsterdam to The Hague

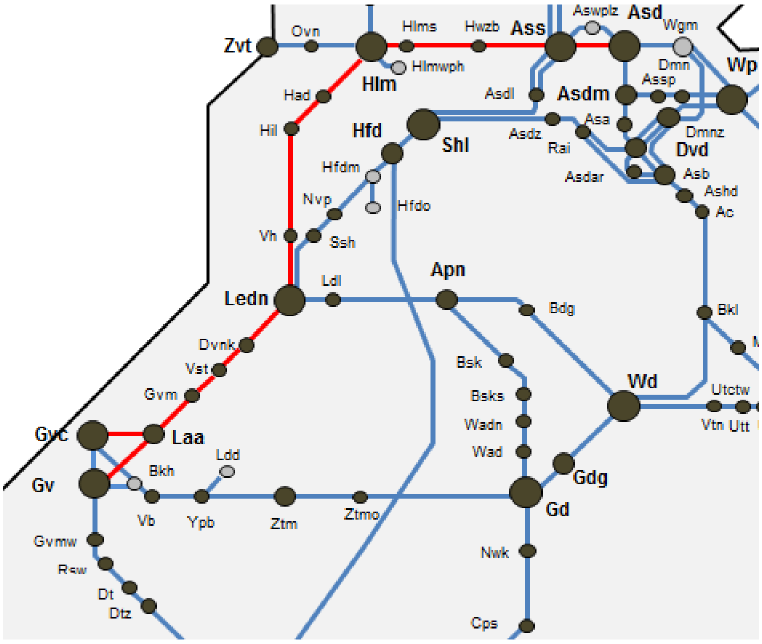

Figure i.3: 'Oude Lijn' from Amsterdam to The Hague indicated by red in the Dutch railway network.

i. 14 Stations are served by NS (Gv, Gvc, Laa, Gvm, Vst, Dvnk, Ledn, Vh, Hil, Had, Hlm, Hlms, Hwzb & Ass) and 1 station (Asd) is served by NS and various international operators such as Thalys and DB. There are no stations or routes within the sub network which are served exclusively by other operators (considering NS and its international daughter company as one joint organisation). Thalys and DB only offer services from outside the sub network to the major transfer hub at the edge of the sub network.

ii. The network holds 15 nodes and 28 arcs. There are Confidential data during the morning rush hour.

iii. The network does not allow for rerouting, at least not in the way that the sub network is defined now. If the Schiphol railway line would be included, there are some options for rerouting.

iv. The network has one location diverging or converging branches: The Hague Laan van NOI.

v. The network has many through-going passengers, for example on international routes between Belgium and the Randstad area and on interurban routes within the Randstad. Furthermore, there are many options for passengers to transfer to different parts of the railway network.

i.4 Noord-Holland north of the North Sea Channel

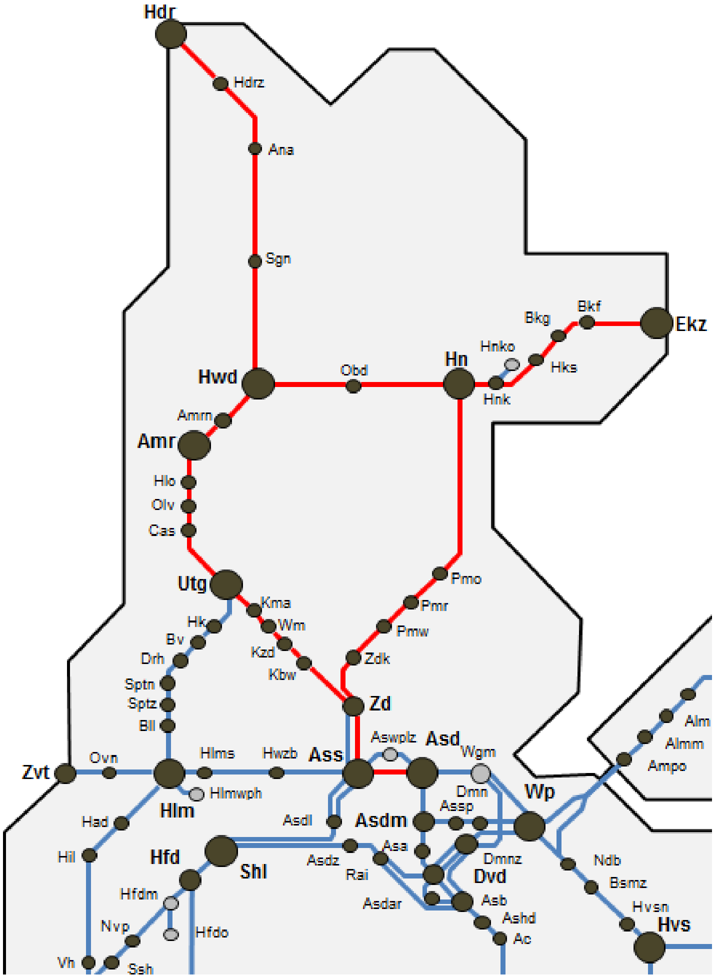

Figure i.4: Sub-network in Noord-Holland north of the North Sea Channel indicated by red in the Dutch railway network.

i. 27 Stations are served by NS (Ass, Zd, Kbw, Kzd, Wm, Kma, Utg, Cas, Hlo, Amr, Amrn, Hwd, Sgn, Ana, Hdrz, Hdr, Obd, Hn, Hnk, Hks, Bkg, Bkf, Ekz, Pmo, Pmr, Pmw & Zdk), 1 station (Asd) is served by NS and various international operators such as Thalys and DB and 1 station used to be open during special events only (Olv). There are no stations or routes within the sub network which are served exclusively by other operators.

ii. The network holds 28 nodes (when excluding Olv) and 56 arcs. There are Confidential data Confidential data during the morning rush hour.

iii. The network allows for rerouting between some of the outermost parts of the network. Local relations have rerouting options which come at the cost of large detours. Naturally, the branches from Den Helder to Heerhugowaard, Amsterdam to Zaandam and Enkhuizen to Hoorn do not offer rerouting possibilities.

iv. The network has three locations of diverging or converging branches: Heerhugowaard, Hoorn and Zaandam.

v. The network has a very strong focus on Amsterdam and has a distinct peak hour direction of passenger flow. During the morning rush hour, commuters travel towards Amsterdam, while passengers return home during the evening. Major passenger flows out of the sub network are towards and from Schiphol Airport, Haarlem and Utrecht.

i.5 Star network around Utrecht

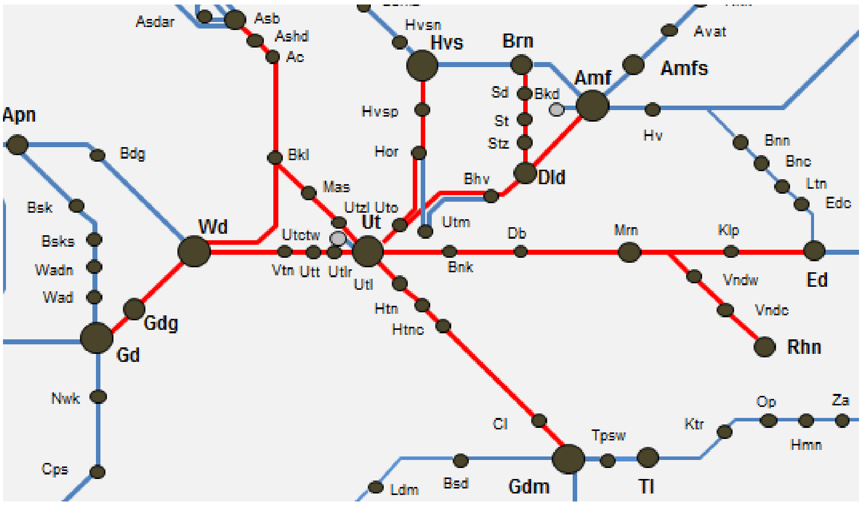

Figure i.5: Star network around Utrecht indicated by red in the Dutch railway network.

i. 33 Stations are served by NS or subsidiaries (Gd, Gdg, Wd, Vtn, Utt, Utlr, Utl, Htn, Htnc, Cl, Bnk, Db, Mrn, Klp, Vndw, Vndc, Rhn, Uto, Hor, Hvsp, Hvs, Bhv, Dld, Stz, St, Sd, Brn, Utzl, Mas, Bkl, Ac, Ashd & Asb), 1 station (Ut) is served by NS and various international operators such as DB, 1 station (Gdm) is served by NS and Arriva and 2 stations (Amf & Ed) are served by NS and Connexxion. There are no stations or routes within the sub network which are served exclusively by other operators.

ii. The network holds 37 nodes and 74 arcs. The number of passenger request within the sub network cannot be stated without making major assumptions on routing of through-going passengers.

iii. The network does not allow for any rerouting, except for some stations along the branches from Utrecht to Amsterdam Bijlmer and Gouda.

iv. The network has six locations of diverging or converging branches: Woerden, Breukelen, Utrecht Centraal, Utrecht Overvecht, Den Dolder and Maarn.

v. The network has a very strong focus on Utrecht Centraal. Simultaneously the network is part of various national railway corridors, such as the busy route from Amsterdam to Eindhoven and Rotterdam to Zwolle.

i.6 Triangle Rotterdam – The Hague - Gouda

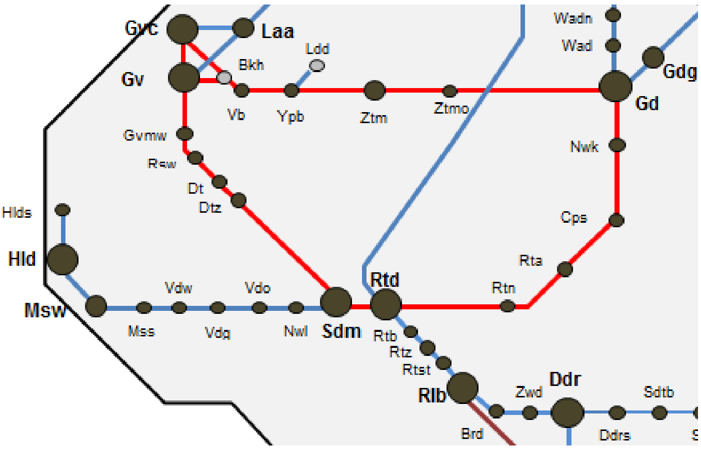

Figure i.6: Triangle Rotterdam – The Hague - Gouda indicated by red in the Dutch railway network.

i. 16 Stations are served by NS or subsidiaries (Rtn, Rta, Cps, Nwk, Gd, Ztmo, Ztm, Ypb, Vb, Gvc, Gv, Gvmw, Rsw, Dt, Dtz & Sdm) and 1 station (Rtd) is served by NS and international operator Thalys. There are no stations or routes within the sub network which are served exclusively by other operators

ii. The network holds 17 nodes and 36 arcs. The number of passenger request within the sub network cannot be stated without making major assumptions on routing of through-going passengers.

iii. The network allows for rerouting, because it has a circular structure. Route options may differ in length significantly.

iv. The network has two locations of diverging or converging branches: The Hague HS and Voorburg.

v. The network is part of one of the busiest train corridors in the Randstad area. Multiple busy routes traverse through the network, such as Leiden – Dordrecht, The Hague – Utrecht and Rotterdam – Utrecht.

i.7 Area bound by Utrecht, Breda and Eindhoven

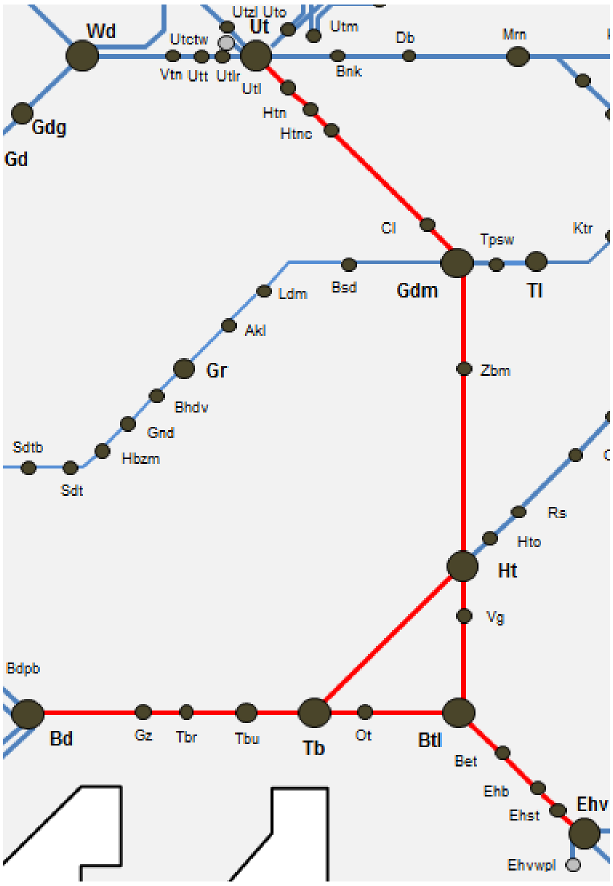

Figure i.7: Area bound by Utrecht, Breda and Eindhoven indicated by red in the Dutch railway network.

i. 17 Stations are served by NS or subsidiaries (Bd, Gz, Tbr, Tbu, Tb, Ot, Btl, Bet, Ehb, Ehv, Vg, Ht, Zbm, Cl, Htnc, Htn & Utl), 1 station (Ut) is served by NS and international operators such as DB, 1 station (Gdm) is served by NS and Arriva and 1 station is used for events only (Ehst). There are no stations or routes within the sub network which are served exclusively by other operators.

ii. The network holds 19 nodes and 38 arcs (when excluding Ehst). The number of passenger request within the sub network cannot be stated without making major assumptions on routing of through-going passengers.

iii. The network allows for rerouting on a very small scale, because the majority of all stations are on the branches stretching out from the triangular centre of the network.

iv. The network has three locations of diverging or converging branches: Den Bosch, Tilburg and Boxtel.

v. Many passengers travel between the three major cities in Brabant. Also, the busy corridor from Eindhoven to Utrecht is fully included in the network. On the other hand, various long-distance routes are cut in the middle, such as Amsterdam – Maastricht and The Hague – Venlo. Moreover, cargo transport has a significant share in the railway utilization in this area.

Appendix J – Level of service comparison in the case study area

Table J.1a: Travel time and frequency comparison between all OD-pairs which are served in the rail DRT-system.

OD-pair				Rail DRT		2016 Time table		Comparison	
O	**D**	**Distance [km]**	**Demand [pax/hr]**	**Travel time [minutes]**	**Hourly frequency**	**Travel time [minutes]**	**Hourly Frequency**	**Travel time difference per pax**	**Cumulative travel time difference**
Amr	Asd	41	Confidential data	33	13	34	4	1.5	Confidential data
Amr	Ass	36		28	12	28	4	-0.1	
Amr	Hdr	40		36	1	36	2	0.4	
Amr	Hn	23		17	2	23	2	6.0	
Amr	Hwd	7		5	2	7	4	1.6	
Amr	Sgn	21		22	2	17	2	-5.2	
Amr	Zd	29		22	3	22	4	0.5	
Amrn	Asd	43		35	5	44	2	9.0	
Amrn	Ass	38		30	5	38	2	8.3	
Amrn	Hn	22		12	1	21	2	9.0	
Amrn	Hwd	5		4	1	5	2	0.9	
Amrn	Zd	31		19	1	32	2	13.0	
Ana	Amr	30		23	2	24	2	1.2	
Ana	Sgn	9		10	5	6	2	-3.8	
Asd	Amr	42		31	6	34	4	2.6	
Asd	Amrn	44		28	1	44	2	16.3	
Asd	Ass	5		4	14	5	12	0.6	
Asd	Cas	30		23	2	25	4	2.5	
Asd	Hlo	37		24	1	31	2	6.9	
Asd	Hn	45		37	4	35	2	-1.8	
Asd	Hnk	47		27	1	42	2	15.4	
Asd	Hwd	49		31	1	49	2	17.9	
Asd	Kbw	14		8	1	15	4	7.1	
Asd	Kma	21		14	2	25	4	11.3	
Asd	Kzd	15		10	2	18	4	8.0	
Asd	Utg	26		26	2	29	4	2.6	
Asd	Wm	18		15	2	21	4	5.7	
Asd	Zd	12		9	12	12	8	3.0	
Ass	Amr	37		32	5	28	4	-3.9	
Ass	Amrn	39		24	1	38	2	13.7	
Ass	Asd	5		5	7	5	10	0.1	
Ass	Cas	25		16	1	19	4	3.3	
Ass	Hn	40		35	3	27	4	-7.5	
Ass	Hnk	42		26	1	34	4	7.8	
Ass	Hwd	44		31	1	43	2	11.9	
Ass	Kma	16		14	2	19	4	4.7	
Ass	Utg	22		16	1	24	4	7.6	
Ass	Wm	13		14	2	16	4	1.7	
Ass	Zd	7		6	8	6	8	0.3	

Table J.1b: Travel time and frequency comparison between all OD-pairs which are served in the rail DRT-system (continuation of table J.1a).

OD-pair				Rail DRT		2016 Time table		Comparison	
O	D	Distance [km]	Demand [pax/hr]	Travel time [minutes]	Hourly frequency	Travel time [minutes]	Hourly Frequency	Travel time difference per pax	Cumulative travel time difference
Bkf	Hn	16	[redacted]	17	1	19	4	2.3	[redacted]
Bkg	Asd	59	[redacted]	61	3	52	4	-8.8	[redacted]
Bkg	Ass	54	[redacted]	52	2	44	4	-7.6	[redacted]
Bkg	Hn	15	[redacted]	15	3	15	4	0.1	[redacted]
Cas	Amr	12	[redacted]	10	3	9	4	-1.0	[redacted]
Cas	Asd	29	[redacted]	22	7	25	4	2.5	[redacted]
Cas	Ass	24	[redacted]	20	7	19	4	-1.2	[redacted]
Cas	Zd	17	[redacted]	16	2	13	4	-2.7	[redacted]
Ekz	Asd	62	[redacted]	57	2	61	4	4.1	[redacted]
Ekz	Ass	57	[redacted]	71	2	53	4	-17.8	[redacted]
Ekz	Hn	18	[redacted]	24	3	24	4	-0.1	[redacted]
Hdr	Amr	41	[redacted]	40	3	35	2	-4.9	[redacted]
Hdr	Asd	82	[redacted]	64	1	76	2	12.0	[redacted]
Hdr	Hwd	34	[redacted]	23	1	27	2	3.6	[redacted]
Hdr	Sgn	20	[redacted]	19	3	17	2	-1.9	[redacted]
Hdrz	Amr	39	[redacted]	27	2	31	2	3.7	[redacted]
Hdrz	Ass	75	[redacted]	61	1	66	2	4.8	[redacted]
Hdrz	Sgn	18	[redacted]	20	2	13	2	-6.9	[redacted]
Hks	Amr	34	[redacted]	27	1	40	2	12.7	[redacted]
Hks	Asd	55	Confidential	51	3	48	4	-2.8	Confidential
Hks	Ass	50	data	52	3	40	4	-12.2	data
Hks	Hn	11	[redacted]	10	2	11	4	0.9	[redacted]
Hlo	Amr	5	[redacted]	4	1	6	4	2.5	[redacted]
Hlo	Asd	36	[redacted]	30	5	31	2	1.4	[redacted]
Hlo	Ass	31	[redacted]	28	5	25	2	-2.5	[redacted]
Hlo	Hwd	12	[redacted]	8	1	18	4	10.1	[redacted]
Hlo	Zd	24	[redacted]	14	1	19	2	5.1	[redacted]
Hn	Amr	24	[redacted]	19	5	25	2	6.0	[redacted]
Hn	Asd	44	[redacted]	34	12	33	4	-1.2	[redacted]
Hn	Ass	40	[redacted]	32	11	25	6	-6.6	[redacted]
Hn	Ekz	17	[redacted]	35	1	23	2	-11.6	[redacted]
Hn	Hwd	17	[redacted]	14	3	17	2	3.1	[redacted]
Hn	Pmo	18	[redacted]	12	1	11	2	-1.2	[redacted]
Hn	Pmr	19	[redacted]	14	1	14	2	0.2	[redacted]
Hn	Zd	33	[redacted]	27	2	26	2	-1.1	[redacted]
Hnk	Amr	26	[redacted]	22	2	33	2	10.6	[redacted]
Hnk	Asd	47	[redacted]	38	7	41	4	3.3	[redacted]
Hnk	Ass	42	[redacted]	37	7	33	4	-3.9	[redacted]
Hnk	Zd	35	[redacted]	22	1	32	2	10.1	[redacted]
Hwd	Amr	7	[redacted]	7	3	8	2	0.7	[redacted]
Hwd	Asd	48	[redacted]	45	5	49	2	4.3	[redacted]

Table J.1c: Travel time and frequency comparison between all OD-pairs which are served in the rail DRT-system (continuation of table J.1b).

OD-pair				Rail DRT		2016 Time table		Comparison	
O	D	Distance [km]	Demand [pax/hr]	Travel time [minutes]	Hourly frequency	Travel time [minutes]	Hourly Frequency	Travel time difference per pax	Cumulative travel time difference
Hwd	Ass	43	[redacted]	39	5	43	2	3.9	[redacted]
Hwd	Hdr	33	[redacted]	28	1	28	2	-0.2	[redacted]
Hwd	Hn	17	[redacted]	15	3	16	2	1.0	[redacted]
Hwd	Sgn	14	[redacted]	8	1	9	2	0.5	[redacted]
Hwd	Zd	36	[redacted]	26	1	37	2	10.5	[redacted]
Kbw	Asd	14	[redacted]	10	4	16	4	5.5	[redacted]
Kbw	Ass	9	[redacted]	9	4	10	4	1.1	[redacted]
Kma	Amr	21	[redacted]	15	1	33	2	18.4	[redacted]
Kma	Asd	20	[redacted]	16	7	25	4	8.6	[redacted]
Kma	Ass	15	[redacted]	14	7	19	4	5.2	[redacted]
Kma	Zd	8	[redacted]	7	3	13	4	6.5	[redacted]
Kzd	Asd	15	[redacted]	12	4	18	4	5.8	[redacted]
Kzd	Ass	10	[redacted]	11	3	12	4	1.5	[redacted]
Obd	Amr	13	[redacted]	12	3	14	2	1.6	[redacted]
Obd	Hn	11	[redacted]	6	1	9	2	3.2	[redacted]
Pmo	Ass	22	[redacted]	16	2	20	2	3.8	[redacted]
Pmo	Hn	18	[redacted]	11	1	12	2	0.8	[redacted]
Pmo	Zd	15	[redacted]	12	2	15	2	2.6	[redacted]
Pmr	Ass	20	Confidential data	19	3	17	2	-1.6	Confidential data
Pmr	Hn	19	[redacted]	10	1	14	2	4.1	[redacted]
Pmr	Zd	13	[redacted]	9	2	12	2	3.1	[redacted]
Pmw	Ass	19	[redacted]	13	2	15	2	2.4	[redacted]
Pmw	Zd	12	[redacted]	10	2	10	2	-0.4	[redacted]
Sgn	Amr	21	[redacted]	17	5	18	2	1.0	[redacted]
Sgn	Asd	62	[redacted]	42	2	59	2	17.4	[redacted]
Sgn	Ass	57	[redacted]	40	2	53	2	12.9	[redacted]
Sgn	Hdr	19	[redacted]	21	2	19	2	-1.6	[redacted]
Sgn	Hwd	14	[redacted]	11	2	10	2	-0.6	[redacted]
Utg	Amr	16	[redacted]	15	3	15	2	-0.4	[redacted]
Utg	Asd	25	[redacted]	22	6	29	4	7.5	[redacted]
Utg	Ass	20	[redacted]	16	5	23	4	7.1	[redacted]
Utg	Zd	13	[redacted]	13	2	17	4	4.0	[redacted]
Wm	Asd	18	[redacted]	15	5	22	4	6.9	[redacted]
Wm	Ass	13	[redacted]	12	5	16	4	3.8	[redacted]
Wm	Zd	6	[redacted]	4	1	10	4	5.9	[redacted]
Zd	Amr	30	[redacted]	29	3	22	4	-7.2	[redacted]
Zd	Asd	12	[redacted]	10	16	12	8	2.0	[redacted]
Zd	Ass	7	[redacted]	6	12	6	10	0.0	[redacted]
Zd	Kma	9	[redacted]	6	1	13	4	6.7	[redacted]

Appendix K – Base case scenario results

Table K.1: Track capacity and vehicle flow per arc in the grid network.

Node arc start	Node arc end	Capacity [tracks]		Flow [veh/hr]		Utilization		Node arc start	Node arc end	Capacity [tracks]		Flow [veh/hr]		Utilization	
		Initial	Final	Initial	Final	Initial	Final			Initial	Final	Initial	Final	Initial	Final
1	*3*	0.86	0.82	100	100	0.65	0.68	*3*	*1*	0.86	0.82	100	101	0.65	0.69
1	*5*	0.86	1.25	100	155	0.65	0.69	*5*	*1*	0.86	1.26	100	155	0.65	0.69
1	*7*	0.86	0.81	100	100	0.65	0.68	*7*	*1*	0.86	0.82	100	101	0.65	0.69
1	*9*	0.86	1.26	100	157	0.65	0.69	*9*	*1*	0.86	1.25	100	155	0.65	0.69
3	*2*	0.70	0.36	81	45	0.65	0.69	*2*	*3*	0.70	0.37	81	45	0.65	0.68
3	*4*	0.70	0.36	81	45	0.65	0.69	*4*	*3*	0.70	0.36	81	45	0.65	0.69
3	*11*	0.83	0.69	97	86	0.65	0.69	*11*	*3*	0.83	0.69	97	87	0.65	0.70
5	*4*	0.70	0.67	81	82	0.65	0.68	*4*	*5*	0.70	0.67	81	82	0.65	0.68
5	*6*	0.70	0.66	81	82	0.65	0.69	*6*	*5*	0.70	0.66	81	82	0.65	0.69
5	*13*	0.83	0.91	97	111	0.65	0.68	*13*	*5*	0.83	0.91	97	111	0.65	0.68
7	*6*	0.70	0.37	81	45	0.65	0.68	*6*	*7*	0.70	0.37	81	45	0.65	0.68
7	*8*	0.70	0.36	81	45	0.65	0.69	*8*	*7*	0.70	0.37	81	45	0.65	0.68
7	*15*	0.83	0.69	97	86	0.65	0.69	*15*	*7*	0.83	0.69	97	87	0.65	0.70
9	*2*	0.70	0.67	81	82	0.65	0.68	*2*	*9*	0.70	0.66	81	82	0.65	0.69
9	*8*	0.70	0.67	81	82	0.65	0.68	*8*	*9*	0.70	0.66	81	82	0.65	0.69
9	*17*	0.83	0.91	97	113	0.65	0.69	*17*	*9*	0.83	0.91	97	111	0.65	0.68
10	*11*	0.17	0.10	20	13	0.65	0.72	*11*	*10*	0.17	0.10	20	12	0.65	0.67
11	*12*	0.17	0.10	20	13	0.65	0.72	*12*	*11*	0.17	0.10	20	13	0.65	0.72
12	*13*	0.17	0.21	20	25	0.65	0.67	*13*	*12*	0.17	0.21	20	25	0.65	0.67
13	*14*	0.17	0.21	20	25	0.65	0.67	*14*	*13*	0.17	0.21	20	25	0.65	0.67
14	*15*	0.17	0.10	20	13	0.65	0.72	*15*	*14*	0.17	0.10	20	13	0.65	0.72
15	*16*	0.17	0.10	20	12	0.65	0.67	*16*	*15*	0.17	0.10	20	13	0.65	0.72
16	*17*	0.17	0.21	20	25	0.65	0.67	*17*	*16*	0.17	0.21	20	26	0.65	0.70
17	*10*	0.17	0.21	20	26	0.65	0.70	*10*	*17*	0.17	0.21	20	25	0.65	0.67

Table K.2: Track capacity and vehicle flow per arc in the ring/radial network.

Node	Node	Capacity [tracks]		Flow [veh/hr]		Utilization		Node	Node	Capacity [tracks]		Flow [veh/hr]		Utilization	
arc start	**arc end**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**arc start**	**arc end**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
1	*2*	0.61	0.82	71	101	0.65	0.69	*2*	*1*	0.61	0.82	71	101	0.65	0.69
1	*3*	0.98	1.24	114	153	0.65	0.69	*3*	*1*	0.98	1.24	114	153	0.65	0.69
1	*4*	0.61	0.82	71	101	0.65	0.69	*4*	*1*	0.61	0.82	71	101	0.65	0.69
1	*5*	0.98	1.24	114	153	0.65	0.69	*5*	*1*	0.98	1.24	114	153	0.65	0.69
1	*6*	0.61	0.82	71	101	0.65	0.69	*6*	*1*	0.61	0.82	71	101	0.65	0.69
1	*7*	0.98	1.24	114	153	0.65	0.69	*7*	*1*	0.98	1.24	114	153	0.65	0.69
1	*8*	0.61	0.82	71	101	0.65	0.69	*8*	*1*	0.61	0.82	71	101	0.65	0.69
1	*9*	0.98	1.24	114	153	0.65	0.69	*9*	*1*	0.98	1.24	114	153	0.65	0.69
2	*10*	0.32	0.31	38	38	0.65	0.69	*10*	*2*	0.32	0.31	38	38	0.65	0.69
2	*11*	0.38	0.18	44	22	0.65	0.69	*11*	*2*	0.38	0.18	44	22	0.65	0.69
2	*17*	0.38	0.18	44	22	0.65	0.69	*17*	*2*	0.38	0.18	44	22	0.65	0.69
3	*11*	0.57	0.33	66	41	0.65	0.69	*11*	*3*	0.57	0.33	66	41	0.65	0.69
4	*11*	0.38	0.18	44	22	0.65	0.69	*11*	*4*	0.38	0.18	44	22	0.65	0.69
4	*12*	0.32	0.31	38	38	0.65	0.69	*12*	*4*	0.32	0.31	38	38	0.65	0.69
4	*13*	0.38	0.18	44	22	0.65	0.69	*13*	*4*	0.38	0.18	44	22	0.65	0.69
5	*13*	0.57	0.33	66	41	0.65	0.69	*13*	*5*	0.57	0.33	66	41	0.65	0.69
6	*13*	0.38	0.18	44	22	0.65	0.69	*13*	*6*	0.38	0.18	44	22	0.65	0.69
6	*14*	0.32	0.31	38	38	0.65	0.69	*14*	*6*	0.32	0.31	38	38	0.65	0.69
6	*15*	0.38	0.18	44	22	0.65	0.69	*15*	*6*	0.38	0.18	44	22	0.65	0.69
7	*15*	0.57	0.33	66	41	0.65	0.69	*15*	*7*	0.57	0.33	66	41	0.65	0.69
8	*15*	0.38	0.18	44	22	0.65	0.69	*15*	*8*	0.38	0.18	44	22	0.65	0.69
8	*16*	0.32	0.31	38	38	0.65	0.69	*16*	*8*	0.32	0.31	38	38	0.65	0.69
8	*17*	0.38	0.18	44	22	0.65	0.69	*17*	*8*	0.38	0.18	44	22	0.65	0.69
9	*17*	0.57	0.33	66	41	0.65	0.69	*17*	*9*	0.57	0.33	66	41	0.65	0.69

Table K.3: Platform capacity per node in the grid network.

	Initial						Final					
Node nr.	**Capacity**	**Utilization**	**Dwelling vehicles**		**Non-stop vehicles**		**Capacity**	**Utilization**	**Dwelling vehicles**		**Non-stop vehicles**	
1	13.31	65%	376	(64%)	212	(36%)	10.08	87%	376	(54%)	324	(46%)
2	8.76	65%	254	(88%)	36	(12%)	6.65	85%	254	(100%)	0	(0%)
3	11.50	65%	324	(62%)	198	(38%)	8.51	86%	324	(74%)	115	(26%)
4	8.76	65%	254	(88%)	36	(12%)	6.65	85%	254	(100%)	0	(0%)
5	11.50	65%	324	(62%)	198	(38%)	8.76	86%	324	(55%)	268	(45%)
6	8.76	65%	254	(88%)	36	(12%)	6.65	85%	254	(100%)	0	(0%)
7	11.50	65%	324	(62%)	198	(38%)	8.51	86%	324	(74%)	115	(26%)
8	8.76	65%	254	(88%)	36	(12%)	6.65	85%	254	(100%)	0	(0%)
9	11.50	65%	324	(62%)	198	(38%)	8.76	87%	324	(55%)	270	(45%)
10	2.60	65%	76	(98%)	2	(2%)	2.22	76%	76	(100%)	0	(0%)
11	5.92	65%	170	(77%)	52	(23%)	4.64	82%	170	(86%)	27	(14%)
12	2.60	65%	76	(98%)	2	(2%)	2.22	76%	76	(100%)	0	(0%)
13	5.92	65%	170	(77%)	52	(23%)	4.73	82%	170	(69%)	76	(31%)
14	2.60	65%	76	(98%)	2	(2%)	2.22	76%	76	(100%)	0	(0%)
15	5.92	65%	170	(77%)	52	(23%)	4.64	82%	170	(86%)	27	(14%)
16	2.60	65%	76	(98%)	2	(2%)	2.22	76%	76	(100%)	0	(0%)
17	5.92	65%	170	(77%)	52	(23%)	4.73	82%	170	(69%)	78	(31%)

Table K.4: Platform capacity per node in the ring/radial network.

	Initial						Final					
Node nr.	**Capacity**	**Utilization**	**Dwelling vehicles**		**Non-stop vehicles**		**Capacity**	**Utilization**	**Dwelling vehicles**		**Non-stop vehicles**	
1	14.04	65%	376	(40%)	555	(60%)	10.86	88%	376	(31%)	828	(69%)
2	8.84	65%	254	(78%)	71	(22%)	6.74	85%	254	(82%)	56	(18%)
3	11.12	65%	324	(95%)	18	(5%)	8.38	86%	324	(91%)	32	(9%)
4	8.84	65%	254	(78%)	71	(22%)	6.74	85%	254	(82%)	56	(18%)
5	11.12	65%	324	(95%)	18	(5%)	8.38	86%	324	(91%)	32	(9%)
6	8.84	65%	254	(78%)	71	(22%)	6.74	85%	254	(82%)	56	(18%)
7	11.12	65%	324	(95%)	18	(5%)	8.38	86%	324	(91%)	32	(9%)
8	8.84	65%	254	(78%)	71	(22%)	6.74	85%	254	(82%)	56	(18%)
9	11.12	65%	324	(95%)	18	(5%)	8.38	86%	324	(91%)	32	(9%)
10	2.60	65%	76	(100%)	0	(0%)	2.22	76%	76	(100%)	0	(0%)
11	5.96	65%	170	(71%)	70	(29%)	4.59	82%	170	(100%)	0	(0%)
12	2.60	65%	76	(100%)	0	(0%)	2.22	76%	76	(100%)	0	(0%)
13	5.96	65%	170	(71%)	70	(29%)	4.59	82%	170	(100%)	0	(0%)
14	2.60	65%	76	(100%)	0	(0%)	2.22	76%	76	(100%)	0	(0%)
15	5.96	65%	170	(71%)	70	(29%)	4.59	82%	170	(100%)	0	(0%)
16	2.60	65%	76	(100%)	0	(0%)	2.22	76%	76	(100%)	0	(0%)
17	5.96	65%	170	(71%)	70	(29%)	4.59	82%	170	(100%)	0	(0%)

Table K.5a: Flow distribution over the available route options per OD-pair in the gird network. This table contains all OD-pairs of which the vehicle flow is routed via multiple route options. The routes are shown as the sequence of nodes traversed along it. Route length is expressed in free flow travel time in units of hours.

O	*D*	Options	Route	Length	Share	Route	Length	Share	Route	Length	Share	Route	Length	Share
2	*6*	10	[2 3 1 5 6]	0.24	2%	[2 3 4 5 1 7 6]	0.36	0%	[2 9 1 3 4 5 6]	0.36	0%	[2 9 8 7 1 5 6]	0.36	0%
			[2 3 1 7 6]	0.24	1%	[2 3 4 5 6]	0.24	0%	[2 9 1 5 6]	0.24	95%	[2 9 8 7 6]	0.24	0%
			[2 3 1 9 8 7 6]	0.36	0%				[2 9 1 7 6]	0.24	2%			
4	*8*	10	[4 3 1 5 6 7 8]	0.36	0%	[4 3 2 9 1 7 8]	0.36	0%	[4 5 1 3 2 9 8]	0.36	0%	[4 5 6 7 1 9 8]	0.36	0%
			[4 3 1 7 8]	0.24	1%	[4 3 2 9 8]	0.24	0%	[4 5 1 7 8]	0.24	2%	[4 5 6 7 8]	0.24	0%
			[4 3 1 9 8]	0.24	2%				[4 5 1 9 8]	0.24	95%			
6	*2*	10	[6 5 1 3 2]	0.24	2%	[6 5 4 3 1 9 2]	0.36	0%	[6 7 1 3 2]	0.24	1%	[6 7 8 9 1 3 2]	0.36	0%
			[6 5 1 7 8 9 2]	0.36	0%	[6 5 4 3 2]	0.24	0%	[6 7 1 5 4 3 2]	0.36	0%	[6 7 8 9 2]	0.24	0%
			[6 5 1 9 2]	0.24	95%				[6 7 1 9 2]	0.24	2%			
8	*4*	10	[8 7 1 3 4]	0.24	1%	[8 7 6 5 1 3 4]	0.36	0%	[8 9 1 3 4]	0.24	2%	[8 9 2 3 1 5 4]	0.36	0%
			[8 7 1 5 4]	0.24	2%	[8 7 6 5 4]	0.24	0%	[8 9 1 5 4]	0.24	95%	[8 9 2 3 4]	0.24	0%
			[8 7 1 9 2 3 4]	0.36	0%				[8 9 1 7 6 5 4]	0.36	0%			
1	*10*	6	[1 3 2 9 17 10]	0.36	0%	[1 5 4 3 11 10]	0.36	0%	[1 7 8 9 17 10]	0.36	0%	[1 9 2 3 11 10]	0.36	0%
			[1 3 11 10]	0.24	16%							[1 9 17 10]	0.24	84%
1	*12*	6	[1 3 4 5 13 12]	0.36	0%	[1 5 4 3 11 12]	0.36	0%	[1 7 6 5 13 12]	0.36	0%	[1 9 2 3 11 12]	0.36	0%
			[1 3 11 12]	0.24	27%	[1 5 13 12]	0.24	73%						
1	*14*	6	[1 3 4 5 13 14]	0.36	0%	[1 5 6 7 15 14]	0.36	0%	[1 7 6 5 13 14]	0.36	0%	[1 9 8 7 15 14]	0.36	0%
						[1 5 13 14]	0.24	79%	[1 7 15 14]	0.24	21%			
1	*16*	6	[1 3 2 9 17 16]	0.36	0%	[1 5 6 7 15 16]	0.36	0%	[1 7 8 9 17 16]	0.36	0%	[1 9 8 7 15 16]	0.36	0%
									[1 7 15 16]	0.24	17%	[1 9 17 16]	0.24	83%
10	*1*	6	[10 11 3 1]	0.24	26%	[10 17 9 1]	0.24	74%						
			[10 11 3 2 9 1]	0.36	0%	[10 17 9 2 3 1]	0.36	0%						
			[10 11 3 4 5 1]	0.36	0%	[10 17 9 8 7 1]	0.36	0%						
12	*1*	6	[12 11 3 1]	0.24	27%	[12 13 5 1]	0.24	73%						
			[12 11 3 2 9 1]	0.36	0%	[12 13 5 4 3 1]	0.36	0%						
			[12 11 3 4 5 1]	0.36	0%	[12 13 5 6 7 1]	0.36	0%						

O	*D*	Options	Route	Length	Share	Route	Length	Share	Route	Length	Share	Route	Length	Share
14	*1*	6	[14 13 5 1]	0.24	80%	[14 15 7 1]	0.24	20%						
			[14 13 5 4 3 1]	0.36	0%	[14 15 7 6 5 1]	0.36	0%						
			[14 13 5 6 7 1]	0.36	0%	[14 15 7 8 9 1]	0.36	0%						
16	*1*	6	[16 15 7 1]	0.24	27%	[16 17 9 1]	0.24	73%						
			[16 15 7 6 5 1]	0.36	0%	[16 17 9 2 3 1]	0.36	0%						
			[16 15 7 8 9 1]	0.36	0%	[16 17 9 8 7 1]	0.36	0%						
2	*10*	4	[2 3 1 9 17 10]	0.36	0%	[2 3 11 10]	0.24	7%	[2 9 1 3 11 10]	0.36	0%	[2 9 17 10]	0.24	93%
4	*12*	4	[4 3 1 5 13 12]	0.36	0%	[4 3 11 12]	0.24	4%	[4 5 1 3 11 12]	0.36	0%	[4 5 13 12]	0.24	96%
6	*14*	4	[6 5 1 7 15 14]	0.36	0%	[6 5 13 14]	0.24	94%	[6 7 1 5 13 14]	0.36	0%	[6 7 15 14]	0.24	6%
8	*16*	4	[8 7 1 9 17 16]	0.36	0%	[8 7 15 16]	0.24	7%	[8 9 1 7 15 16]	0.36	0%	[8 9 17 16]	0.24	93%
10	*2*	4	[10 11 3 1 9 2]	0.36	0%	[10 11 3 2]	0.24	4%	[10 17 9 1 3 2]	0.36	0%	[10 17 9 2]	0.24	96%
12	*4*	4	[12 11 3 1 5 4]	0.36	0%	[12 11 3 4]	0.24	4%	[12 13 5 1 3 4]	0.36	0%	[12 13 5 4]	0.24	96%
14	*6*	4	[14 13 5 1 7 6]	0.36	0%	[14 13 5 6]	0.24	94%	[14 15 7 1 5 6]	0.36	0%	[14 15 7 6]	0.24	6%
16	*8*	4	[16 15 7 1 9 8]	0.36	0%	[16 15 7 8]	0.24	4%	[16 17 9 1 7 8]	0.36	0%	[16 17 9 8]	0.24	96%
2	*5*	3	[2 3 1 5]	0.18	1%	[2 3 4 5]	0.18	0%	[2 9 1 5]	0.18	99%			
2	*7*	3	[2 3 1 7]	0.18	2%	[2 9 1 7]	0.18	98%	[2 9 8 7]	0.18	0%			
3	*6*	3	[3 1 5 6]	0.18	98%	[3 1 7 6]	0.18	2%	[3 4 5 6]	0.18	0%			
3	*8*	3	[3 1 7 8]	0.18	2%	[3 1 9 8]	0.18	98%	[3 2 9 8]	0.18	0%			
4	*7*	3	[4 3 1 7]	0.18	2%	[4 5 1 7]	0.18	98%	[4 5 6 7]	0.18	0%			
4	*9*	3	[4 3 1 9]	0.18	1%	[4 3 2 9]	0.18	0%	[4 5 1 9]	0.18	99%			
5	*2*	3	[5 1 3 2]	0.18	2%	[5 1 9 2]	0.18	98%	[5 4 3 2]	0.18	0%			
5	*8*	3	[5 1 7 8]	0.18	2%	[5 1 9 8]	0.18	98%	[5 6 7 8]	0.18	0%			
6	*3*	3	[6 5 1 3]	0.18	98%	[6 5 4 3]	0.18	0%	[6 7 1 3]	0.18	2%			
6	*9*	3	[6 5 1 9]	0.18	98%	[6 7 1 9]	0.18	2%	[6 7 8 9]	0.18	0%			
7	*2*	3	[7 1 3 2]	0.18	2%	[7 1 9 2]	0.18	98%	[7 8 9 2]	0.18	0%			
7	*4*	3	[7 1 3 4]	0.18	2%	[7 1 5 4]	0.18	98%	[7 6 5 4]	0.18	0%			
8	*3*	3	[8 7 1 3]	0.18	2%	[8 9 1 3]	0.18	98%	[8 9 2 3]	0.18	0%			
8	*5*	3	[8 7 1 5]	0.18	1%	[8 7 6 5]	0.18	0%	[8 9 1 5]	0.18	99%			
9	*4*	3	[9 1 3 4]	0.18	2%	[9 1 5 4]	0.18	98%	[9 2 3 4]	0.18	0%			
9	*6*	3	[9 1 5 6]	0.18	98%	[9 1 7 6]	0.18	2%	[9 8 7 6]	0.18	0%			

Table K.5b: Flow distribution over the available route options per OD-pair in the grid network. This table contains the OD-pairs of which all vehicle flow is routed via one route option. The routes are shown as the sequence of nodes traversed along it. Route length is expressed in free flow travel time in units of hours.

O	*D*	Options	Route	Length	Share	Route	Length	Share	Route	Length	Share	Route	Length	Share
11	*13*	5	[11 3 1 5 13]	0.24	100%	[11 3 2 9 1 5 13]	0.36	0%	[11 3 4 5 13]	0.24	0%	[11 12 13]	0.24	0%
			[11 3 1 7 6 5 13]	0.36	0%									
11	*17*	5	[11 3 1 7 8 9 17]	0.36	0%	[11 3 2 9 17]	0.24	0%	[11 3 4 5 1 9 17]	0.36	0%	[11 10 17]	0.24	0%
			[11 3 1 9 17]	0.24	100%									
13	*11*	5	[13 5 1 3 11]	0.24	100%	[13 5 4 3 11]	0.24	0%	[13 5 6 7 1 3 11]	0.36	0%	[13 12 11]	0.24	0%
			[13 5 1 9 2 3 11]	0.36	0%									
13	*15*	5	[13 5 1 7 15]	0.24	100%	[13 5 4 3 1 7 15]	0.36	0%	[13 5 6 7 15]	0.24	0%	[13 14 15]	0.24	0%
			[13 5 1 9 8 7 15]	0.36	0%									
15	*13*	5	[15 7 1 3 4 5 13]	0.36	0%	[15 7 6 5 13]	0.24	0%	[15 7 8 9 1 5 13]	0.36	0%	[15 14 13]	0.24	0%
			[15 7 1 5 13]	0.24	100%									
15	*17*	5	[15 7 1 3 2 9 17]	0.36	0%	[15 7 6 5 1 9 17]	0.36	0%	[15 7 8 9 17]	0.24	0%	[15 16 17]	0.24	0%
			[15 7 1 9 17]	0.24	100%									
17	*11*	5	[17 9 1 3 11]	0.24	100%	[17 9 2 3 11]	0.24	0%	[17 9 8 7 1 3 11]	0.36	0%	[17 10 11]	0.24	0%
			[17 9 1 5 4 3 11]	0.36	0%									
17	*15*	5	[17 9 1 5 6 7 15]	0.36	0%	[17 9 2 3 1 7 15]	0.36	0%	[17 9 8 7 15]	0.24	0%	[17 16 15]	0.24	0%
			[17 9 1 7 15]	0.24	100%									
1	*2*	2	[1 3 2]	0.12	0%	[1 9 2]	0.12	100%						
1	*4*	2	[1 3 4]	0.12	0%	[1 5 4]	0.12	100%						
1	*6*	2	[1 5 6]	0.12	100%	[1 7 6]	0.12	0%						
1	*8*	2	[1 7 8]	0.12	0%	[1 9 8]	0.12	100%						
2	*1*	2	[2 3 1]	0.12	0%	[2 9 1]	0.12	100%						
3	*5*	2	[3 1 5]	0.12	100%	[3 4 5]	0.12	0%						
3	*9*	2	[3 1 9]	0.12	100%	[3 2 9]	0.12	0%						
3	*13*	2	[3 1 5 13]	0.18	100%	[3 4 5 13]	0.18	0%						
3	*17*	2	[3 1 9 17]	0.18	100%	[3 2 9 17]	0.18	0%						
4	*1*	2	[4 3 1]	0.12	0%	[4 5 1]	0.12	100%						

O	*D*	Options	Route	Length	Share	Route	Length	Share
5	*3*	2	[5 1 3]	0.12	100%	[5 4 3]	0.12	0%
5	*7*	2	[5 1 7]	0.12	100%	[5 6 7]	0.12	0%
5	*11*	2	[5 1 3 11]	0.18	100%	[5 4 3 11]	0.18	0%
5	*15*	2	[5 1 7 15]	0.18	100%	[5 6 7 15]	0.18	0%
6	*1*	2	[6 5 1]	0.12	100%	[6 7 1]	0.12	0%
7	*5*	2	[7 1 5]	0.12	100%	[7 6 5]	0.12	0%
7	*9*	2	[7 1 9]	0.12	100%	[7 8 9]	0.12	0%
7	*13*	2	[7 1 5 13]	0.18	100%	[7 6 5 13]	0.18	0%
7	*17*	2	[7 1 9 17]	0.18	100%	[7 8 9 17]	0.18	0%
8	*1*	2	[8 7 1]	0.12	0%	[8 9 1]	0.12	100%
9	*3*	2	[9 1 3]	0.12	100%	[9 2 3]	0.12	0%
9	*7*	2	[9 1 7]	0.12	100%	[9 8 7]	0.12	0%
9	*11*	2	[9 1 3 11]	0.18	100%	[9 2 3 11]	0.18	0%
9	*15*	2	[9 1 7 15]	0.18	100%	[9 8 7 15]	0.18	0%
11	*5*	2	[11 3 1 5]	0.18	100%	[11 3 4 5]	0.18	0%
11	*9*	2	[11 3 1 9]	0.18	100%	[11 3 2 9]	0.18	0%
13	*3*	2	[13 5 1 3]	0.18	100%	[13 5 4 3]	0.18	0%
13	*7*	2	[13 5 1 7]	0.18	100%	[13 5 6 7]	0.18	0%
15	*5*	2	[15 7 1 5]	0.18	100%	[15 7 6 5]	0.18	0%
15	*9*	2	[15 7 1 9]	0.18	100%	[15 7 8 9]	0.18	0%
17	*3*	2	[17 9 1 3]	0.18	100%	[17 9 2 3]	0.18	0%
17	*7*	2	[17 9 1 7]	0.18	100%	[17 9 8 7]	0.18	0%

All OD-pairs which have not been listed in table K.5a and K.5b only have one route option, which naturally carries all vehicle flow between the OD-pair.

Table K.6: Flow distribution over the available route options per OD-pair in the ring/radial network. This table contains the OD-pairs of which all vehicle flow is routed via one route option. The routes are shown as the sequence of nodes traversed along it. Route length is expressed in free flow travel time in units of hours.

O	D	Options	Route	Length	Share	Route	Length	Share	Route	Length	Share	Route	Length	Share
3	*13*	4	[3 1 4 13]	0.23	0%	[3 1 5 13]	0.18	100%	[3 1 6 13]	0.23	0%	[3 11 4 13]	0.23	0%
3	*17*	4	[3 1 2 17]	0.23	0%	[3 1 8 17]	0.23	0%	[3 1 9 17]	0.18	100%	[3 11 2 17]	0.23	0%
5	*11*	4	[5 1 2 11]	0.23	0%	[5 1 3 11]	0.18	100%	[5 1 4 11]	0.23	0%	[5 13 4 11]	0.23	0%
5	*15*	4	[5 1 6 15]	0.23	0%	[5 1 7 15]	0.18	100%	[5 1 8 15]	0.23	0%	[5 13 6 15]	0.23	0%
7	*13*	4	[7 1 4 13]	0.23	0%	[7 1 5 13]	0.18	100%	[7 1 6 13]	0.23	0%	[7 15 6 13]	0.23	0%
7	*17*	4	[7 1 2 17]	0.23	0%	[7 1 8 17]	0.23	0%	[7 1 9 17]	0.18	100%	[7 15 8 17]	0.23	0%
9	*11*	4	[9 1 2 11]	0.23	0%	[9 1 3 11]	0.18	100%	[9 1 4 11]	0.23	0%	[9 17 2 11]	0.23	0%
9	*15*	4	[9 1 6 15]	0.23	0%	[9 1 7 15]	0.18	100%	[9 1 8 15]	0.23	0%	[9 17 8 15]	0.23	0%
11	*5*	4	[11 2 1 5]	0.23	0%	[11 3 1 5]	0.18	100%	[11 4 1 5]	0.23	0%	[11 4 13 5]	0.23	0%
11	*9*	4	[11 2 1 9]	0.23	0%	[11 2 17 9]	0.23	0%	[11 3 1 9]	0.18	100%	[11 4 1 9]	0.23	0%
13	*3*	4	[13 4 1 3]	0.23	0%	[13 4 11 3]	0.23	0%	[13 5 1 3]	0.18	100%	[13 6 1 3]	0.23	0%
13	*7*	4	[13 4 1 7]	0.23	0%	[13 5 1 7]	0.18	100%	[13 6 1 7]	0.23	0%	[13 6 15 7]	0.23	0%
15	*5*	4	[15 6 1 5]	0.23	0%	[15 6 13 5]	0.23	0%	[15 7 1 5]	0.18	100%	[15 8 1 5]	0.23	0%
15	*9*	4	[15 6 1 9]	0.23	0%	[15 7 1 9]	0.18	100%	[15 8 1 9]	0.23	0%	[15 8 17 9]	0.23	0%
17	*3*	4	[17 2 1 3]	0.23	0%	[17 2 11 3]	0.23	0%	[17 8 1 3]	0.23	0%	[17 9 1 3]	0.18	100%
17	*7*	4	[17 2 1 7]	0.23	0%	[17 8 1 7]	0.23	0%	[17 8 15 7]	0.23	0%	[17 9 1 7]	0.18	100%
1	*11*	3	[1 2 11]	0.17	0%	[1 3 11]	0.12	100%	[1 4 11]	0.17	0%			
1	*13*	3	[1 4 13]	0.17	0%	[1 5 13]	0.12	100%	[1 6 13]	0.17	0%			
1	*15*	3	[1 6 15]	0.17	0%	[1 7 15]	0.12	100%	[1 8 15]	0.17	0%			
1	*17*	3	[1 2 17]	0.17	0%	[1 8 17]	0.17	0%	[1 9 17]	0.12	100%			
11	*1*	3	[11 2 1]	0.17	0%	[11 3 1]	0.12	100%	[11 4 1]	0.17	0%			
13	*1*	3	[13 4 1]	0.17	0%	[13 5 1]	0.12	100%	[13 6 1]	0.17	0%			
15	*1*	3	[15 6 1]	0.17	0%	[15 7 1]	0.12	100%	[15 8 1]	0.17	0%			
17	*1*	3	[17 2 1]	0.17	0%	[17 8 1]	0.17	0%	[17 9 1]	0.12	100%			
2	*3*	2	[2 1 3]	0.14	100%	[2 11 3]	0.14	0%						
2	*4*	2	[2 1 4]	0.17	100%	[2 11 4]	0.17	0%						
2	*8*	2	[2 1 8]	0.17	100%	[2 17 8]	0.17	0%						

O	*D*	Options	Route	Length	Share	Route	Length	Share
2	*9*	2	[2 1 9]	0.14	100%	[2 17 9]	0.14	0%
3	*2*	2	[3 1 2]	0.14	100%	[3 11 2]	0.14	0%
3	*4*	2	[3 1 4]	0.14	100%	[3 11 4]	0.14	0%
3	*10*	2	[3 1 2 10]	0.23	100%	[3 11 2 10]	0.23	0%
3	*12*	2	[3 1 4 12]	0.23	100%	[3 11 4 12]	0.23	0%
4	*2*	2	[4 1 2]	0.17	100%	[4 11 2]	0.17	0%
4	*3*	2	[4 1 3]	0.14	100%	[4 11 3]	0.14	0%
4	*5*	2	[4 1 5]	0.14	100%	[4 13 5]	0.14	0%
4	*6*	2	[4 1 6]	0.17	100%	[4 13 6]	0.17	0%
5	*4*	2	[5 1 4]	0.14	100%	[5 13 4]	0.14	0%
5	*6*	2	[5 1 6]	0.14	100%	[5 13 6]	0.14	0%
5	*12*	2	[5 1 4 12]	0.23	100%	[5 13 4 12]	0.23	0%
5	*14*	2	[5 1 6 14]	0.23	100%	[5 13 6 14]	0.23	0%
6	*4*	2	[6 1 4]	0.17	100%	[6 13 4]	0.17	0%
6	*5*	2	[6 1 5]	0.14	100%	[6 13 5]	0.14	0%
6	*7*	2	[6 1 7]	0.14	100%	[6 15 7]	0.14	0%
6	*8*	2	[6 1 8]	0.17	100%	[6 15 8]	0.17	0%
7	*6*	2	[7 1 6]	0.14	100%	[7 15 6]	0.14	0%
7	*8*	2	[7 1 8]	0.14	100%	[7 15 8]	0.14	0%
7	*14*	2	[7 1 6 14]	0.23	100%	[7 15 6 14]	0.23	0%
7	*16*	2	[7 1 8 16]	0.23	100%	[7 15 8 16]	0.23	0%
8	*2*	2	[8 1 2]	0.17	100%	[8 17 2]	0.17	0%
8	*6*	2	[8 1 6]	0.17	100%	[8 15 6]	0.17	0%
8	*7*	2	[8 1 7]	0.14	100%	[8 15 7]	0.14	0%
8	*9*	2	[8 1 9]	0.14	100%	[8 17 9]	0.14	0%
9	*2*	2	[9 1 2]	0.14	100%	[9 17 2]	0.14	0%
9	*8*	2	[9 1 8]	0.14	100%	[9 17 8]	0.14	0%
9	*10*	2	[9 1 2 10]	0.23	100%	[9 17 2 10]	0.23	0%
9	*16*	2	[9 1 8 16]	0.23	100%	[9 17 8 16]	0.23	0%
10	*3*	2	[10 2 1 3]	0.23	100%	[10 2 11 3]	0.23	0%

O	*D*	Options	Route	Length	Share	Route	Length	Share
10	*9*	2	[10 2 1 9]	0.23	100%	[10 2 17 9]	0.23	0%
11	*13*	2	[11 3 1 5 13]	0.24	0%	[11 4 13]	0.17	100%
11	*17*	2	[11 2 17]	0.17	100%	[11 3 1 9 17]	0.24	0%
12	*3*	2	[12 4 1 3]	0.23	100%	[12 4 11 3]	0.23	0%
12	*5*	2	[12 4 1 5]	0.23	100%	[12 4 13 5]	0.23	0%
13	*11*	2	[13 4 11]	0.17	100%	[13 5 1 3 11]	0.24	0%
13	*15*	2	[13 5 1 7 15]	0.24	0%	[13 6 15]	0.17	100%
14	*5*	2	[14 6 1 5]	0.23	100%	[14 6 13 5]	0.23	0%
14	*7*	2	[14 6 1 7]	0.23	100%	[14 6 15 7]	0.23	0%
15	*13*	2	[15 6 13]	0.17	100%	[15 7 1 5 13]	0.24	0%
15	*17*	2	[15 7 1 9 17]	0.24	0%	[15 8 17]	0.17	100%
16	*7*	2	[16 8 1 7]	0.23	100%	[16 8 15 7]	0.23	0%
16	*9*	2	[16 8 1 9]	0.23	100%	[16 8 17 9]	0.23	0%
17	*11*	2	[17 2 11]	0.17	100%	[17 9 1 3 11]	0.24	0%
17	*15*	2	[17 8 15]	0.17	100%	[17 9 1 7 15]	0.24	0%

All OD-pairs which have not been listed in table K.6 have one route option, which naturally carries all vehicle flow between the OD-pair.