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Consequences of Automated Transport Systems as Feeder Services to Rail

SBB Fund for Research into Management in the Field of Transport

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Management Summary

This research project aims at addressing the question of how interchange stations between rail and autonomous feeder services (either private or shared cars, autonomous buses) need to be designed and where they should be placed in order to meet best the requirements of customers. Furthermore it is investigated how station density along a rail corridor should develop: should new additional stations be built or should in contrary existing ones be closed such that customers would use a feeder to reach the nearest hub.

The entire project articulates along **four main subsidiary research questions** as specified in *chapter 3*. Beforehand, *chapter 2* provides an analysis of the status quo as well as a brief overview of current academic research in the field under consideration.

Question 1, targeting the land requirements for interchange facilities, especially those connecting rail and private or shared cars (in opposition to autonomous buses in line-based service), is addressed in *chapter 4*. It shows that land requirements can be high in terms of area and that not the average inflow of vehicles to stations is relevant, but the maximum possible inflow allowed by the road network. A bus-based feeder is not confronted with these requirements, as the number of vehicles is first of all much lower and secondly (more important) precisely controllable. This allows tailoring of the interchange facility to the effective needs.

Afterwards, *chapter 5* presents the methodology of the model and the simulation environments used to answer research questions 2 to 4. They are first answered by theoretical test cases in order to evaluate the influence of different parameters. *Chapter 6* presents the results of these theoretical test cases.

With regard to research question 2 addressing the benefits of automation in comparison to the status quo as well as the comparison between car-based and bus-based feeder systems, it can be said that automation of feeder systems itself does not allow for travel time savings. With autonomous buses, travel times can be shortened very little, if the number of lines is significantly increased. Car travel times are significantly lower than those of the bus-based feeder. In absolute numbers, the difference is roughly 5 minutes for stations located centrally with respect to the town.

Question 3 targets the benefits of relocating stations when adopting an autonomous feeder system. It turns out that the optimal location of a station is always downstream of the town centre. Unless extreme parameter combinations are chosen, the optimal location is fairly close to the town. Relative speeds of rail and feeder as well as the parameters of the built environment (form of the town, position of the railway line) have an influence on how far downstream the optimal location is.

With regard to question 4 addressing the station density along a railway corridor, one needs to first make a difference between adding or cancelling station within the same town (long-stretched, parallel to the railway line) and cancelling the station of a town while requiring passengers to use a feeder to travel to the nearest hub. The presence of a second station per town does not yield high travel time gains (for both feeder system car and bus). For the other case, the suitability of cancellation depends on many parameters, of which first and foremost the relative speeds of rail and feeder as well as the station spacing. We find out that where

capacity gains (in terms of slots for long-distance or freight traffic) would be desirable, cancellation is less suitable while on lines where cancellation is suitable, capacity gains are not required.

Chapter 7 contains the analytical formulation of the model that was numerically implemented for the theoretical test cases. It requires a number of simplifying assumptions and can only be used for a car-based feeder in rectangular shaped towns with homogeneous settlement density. For all other cases, either an approximation or a numerical simulation is required. The chapter closes with the derivation of nomograms allowing the calculation of the optimal station location and the achievable travel time savings.

Chapter 8 contains the case studies that have been fixed together with SBB: the corridors Lenzburg – Rotkreuz, Winterthur – Wil and Glarus – Linthal. The most important finding is that the availability of land is a major. In order to allow the interchange to work as specified in response to question 1 (see chapter 4), significant land surfaces are required (several thousand square meters). In many cases, those are not available around the current station locations. The alternatives are on the one hand an underground or on-bridge facility (very costly) and on the other hand the relocation to a space outside the town. The latter involves the use of unbuilt agricultural land. For both alternatives, the political chances are questionable. Particularly the use of agricultural land is a sensitive topic in Switzerland.

Finally, *chapter 9* presents the main conclusions of this research project, which can be summarized as follows:

- The optimal number of stations is generally one per town. Cancelling the only station of a town in general leads to travel time losses for the respective town.

- The optimal station location is always downstream of the town centre. Unless we choose extreme parameter combinations of speed and built environment, it is fairly close to the town centre. This statement is equally valid for both types of autonomous feeders. The further the town stretches away from the railway line, the further downstream the optimal location of the station. This is both valid for railway lines passing outside the towns they serve, as well as for towns which are perpendicular to the railway line.

- If stations are meant to serve as an interchange between rail and a car-based feeder, space requirements are high, as the drop-off facility receiving the arriving cars is not designed for the average inflow but for the maximum peak inflow which can be as high as the saturation flow on the access roads.

- The space required for such a rail-car interchange is not easily available in most towns. Either expensive underground or on-bridge facilities are needed, or the station is relocated outside the town, where unbuilt, agricultural land exists. However, this is likely to create conflicts, as previous projects in the field of transportation have shown.

- A bus-based feeder system does not have the same land use requirements, as it involves far less vehicles and their number is precisely known in advance. The temporal bundling of demand dictated by the train schedule strongly favours bundling of demand on the feeder, too.

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OEM	Original Equipment Manufacturer
TPF	Transports Publics Fribourgeois
ZVB	Zugerland Verkehrsbetriebe

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1 Introduction

The efforts in automating the private vehicles date back to 1960s, when the first cart with radio links, *Stanford Cart*, was developed at the University of Stanford (Earnest, 2012). Thanks to advancements in technology and research in recent years, partly autonomous private cars, produced by OEMs such as Mercedes Benz, BMW or Tesla are already driven on our roads today. Full automation, also known as autonomous or driverless operation, is expected to become reality in the next one or two decades. In addition to the automation of private cars, there have been efforts to automate public transport systems and to benefit from economic and operational advantages such as cost savings due to the elimination of the driver factor, better capacity management resulting from more intermediate vehicle sizing (Sinner et al., 2017). Efforts by PostAuto in the city of Sion, SBB in the city of Zug and TPF to test run autonomous buses especially for last mile service operations are a few examples to mention.

The topic of autonomous vehicles in the context of public transportation, especially to serve as last mile and feeder vehicles to rail is yet new and therefore the preconditions, as well as consequences need to be assessed well in advance. One needs to evaluate if such applications are viable and what outcomes can be expected in urban cores, suburban areas and agglomeration zones of metropolitan areas.

Beside the different perspectives that should be evaluated, such as but not limited to technical and IT requirements for operation as well as acceptance of the population to ride in a driverless vehicles, the impacts of autonomous public, private and shared vehicles on the overall transportation systems and on the built environment need to be analysed. In such an approach, the potential adverse impacts of autonomous vehicles can be mitigated and their positive effects are enhanced in a timely manner.

This research deals with the analysis of autonomous public, private and shared vehicles on the transportation systems as feeder services to rail, the location of railway stations and the impacts on the space around the railway stations in the residential municipalities around Swiss metropolitan agglomerations.

2 Status Quo analysis

For decades, public transport services have been in fierce competition with private cars. Figure 1 (Eurostat, 2016) depicts the modal split for trains, busses and private cars within Europe. In 2013, an average of 82% of overall transportation in Europe was carried out by private cars, while public transport was responsible for a modest share of 18%. The share of private cars in Swiss modal split summed up to 78%, with 22% share of public transport. These numbers do not take into account the shares of walking and cycling.
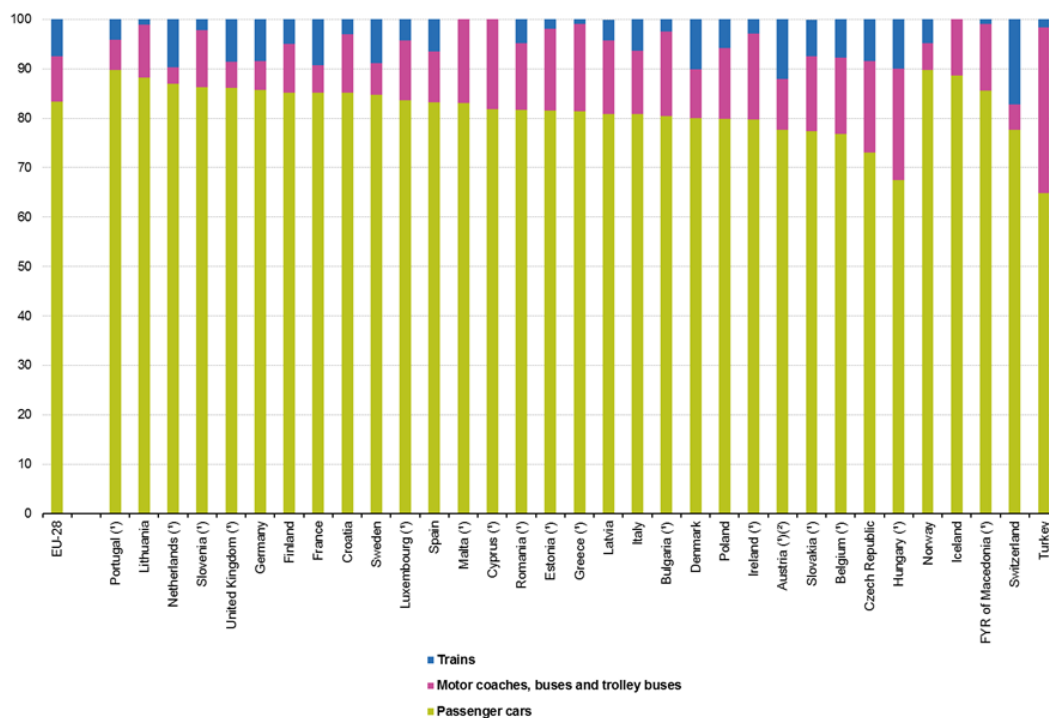
Figure 1: Modal split of inland passenger transport within Europe, 2013 (Eurostat, 2016)

Leaving the advantages of public transport aside, the reasons leading to such low shares of public transport relate to its shortcomings and disadvantages against private vehicles. One strong shortcoming of the public transport systems is the issue of the last mile, which is the first and last step in passengers' daily travel chains. Long walking distances and/or the potential lack of standard cycling facilities between residential locations and the feeder stops are discouraging factors in opting for public transport especially in less densely populated areas and hence, leading to the choice of private vehicles. Another hindrance against the use of public transport is the fact that it is temporally and spatially discrete. Meaning, that the access to public transport services is not ensured overall at any given time and the ones willing to travel need to follow certain timetables or board and alight at certain locations, which may not always be optimal from the passengers' point of view. Other factors against the choice of public transport could be the issues with frequency, reliability, comfort, availability of connection possibilities and availability of information, etc.

On the other hand, there has been an established system of cooperation between public and private transportation systems, meaning that private cars serve as last mile feeders to and from the railway stations. Large Park and Ride (P+R) lots, especially at peripheral railway stations are proofs and facilitators of this cooperation. By enabling the door-to-door transport and together with walking and cycling, private vehicles play the role of last links in daily mobility chains. However, P+R lots consume valuable, centrally located land for high-quality usages. Compared to the number of passengers, P+R brings to the public transport system, it is a very space-consuming type of feeder, unless P+R facilities are arranged multi-deck.

Up until now, the conventional forms of transport systems, including private and public transport systems (shared on-demand services only play a negligible role (Enoch et al., 2006)), in which the vehicles are driven and controlled by human drivers, have dominated the streets and shaped the forms of our cities and agglomerations. However, this might change by the emergence of autonomous vehicles, since the industry is investing large sums in order to bring autonomous vehicles to the market. As one might expect, the ease of use and the elimination of barriers to access such vehicles, such as no further need for a driver's license and enabling the elderly and people with reduced mobility to have access to transport services will change the market and its properties extensively. Furthermore, the providers of public transport services could benefit largely from the fact that they can operate their services without the need for drivers. This will result in considerable savings in personnel costs.

An emerging trend that will have deep impacts on people's behaviours and especially on land use and spatial needs is the concept of shared, free-floating vehicles. In fact they are the most discussed scenario in literature when it comes to autonomous vehicles (Bösch et al., 2016; Fagnant & Kockelman, 2015; Fagnant et al., 2015). The flexibility and ease of their access, provided that adequate fleet sizes are available, make them acceptable alternatives to private cars especially in dense urban areas where the users can reserve and pick up the free-floating cars and leave them wherever they want (UITP, 2015). This ensures the mobility of people with the comfort of private cars without worrying for burdens such as maintenance, insurance, cleaning, gas, etc. Outside urban areas, the continuous and quasi-immediate availability of free-floating, shared cars makes them a serious alternative to public transportation, especially when the latter is running at low frequencies.

2.1 State of technology of autonomous vehicles

In recent years, big OEMs of the automotive industry and technology giants such as Google and Apple have been investing large amounts of money into the development of driverless private cars or pods. However, the emergence of automation has not been and will not be limited to the private vehicles. Start-ups such as Navya and Local Motors have been developing and producing autonomous minibuses that serve as shuttles and feeder services. Two of those shuttles are in service since November 2015 in Sion, Switzerland. Since summer 2017, a mutual pilot project by SBB and ZVB has been launched in the city of Zug and two autonomous shuttles are planned to connect the main station of Zug with Technology Cluster Zug and so the autonomous shuttles are being integrated in existing transport systems (Tagesanzeiger, 2017). The municipality of Marley in agglomeration of Freiburg will be the third

region in Switzerland to start test runs of autonomous shuttles. Finally, in Neuhausen, an autonomous bus line integrated in the existing public transport network shall connect the railway station to the "Rheinfall" (Feusi, 2017).

In Germany the operation of autonomous vehicles as public and shared transport systems is planned as well. German Railways (DB) is operating driverless buses in test routes at the EUREF-Campus in Berlin-Schöneberg (Hunsicker et al., 2017). Similar projects with autonomous shuttles have started in many other cities around the world, but the most advanced and futuristic project would be the one in Singapore, which is in development phase and will come to operation in 2019. The ongoing projects with autonomous vehicles around the world involve minibuses that can carry up to 15 passengers, but in Singapore, the plan is to bring full size 40-seater buses into streets that will serve scheduled transport routes within and outside towns (Tan, 2017). In addition, there is a plan in Singapore for Mobility-on-Demand-Vehicles on the island of Sentosa (Singapore Business Review, 2017).

The extent to which a vehicle can run autonomously is given by the so-called level of automation. Different classification schemes exist in literature, for instance by the (National Highway Traffic Safety Administration (NHTSA) (2013) or the Society of Automotive Engineers (SAE) (2014). The former classifies automation from level 0 to 4, while the latter uses level 0 to 5. For the purposes of the present research project, we assume that the highest possible level of automation is achieved. Vehicles can run fully driverless on all sections of the road network.

2.2   The last mile issue in public transportation

The last mile trips, as the last loops in daily railway journey chains consist of the trips from one's home to the railway station and vice versa. In today's transport systems, the last mile trips to and from the railway stations are done either by walking or cycling in non-motorized forms and/or by private cars or public transport vehicles such as trams and buses in motorized forms. A combination of motorized and non-motorized forms is typical in carrying out the last mile trips. For instance, a trip chain consisting of walking to the bus stop followed by taking the bus to the railway station and fulfilling the main leg of the journey with railway is a typical pattern in our daily transportation. The same pattern is also valid from the destination railway station to the final destination.

Such trip chains have resulted in the application of buses and minibuses, especially in residential areas of agglomeration, as the feeders to the railway stations. A closer look at the regional bus networks of the agglomerations reveals the orientation of regional bus lines towards the railway stations (Figure 2).

The function as a feeder and the orientation of the regional bus networks towards the rail, results in special conditions in the design of the bus lines and infrastructure, which are:

1. Arrival and departure of bus lines are synchronized with the train schedules, meaning that buses arrive at and depart from the railway station in a way that the transfers between rail and feeders are ensured. In other words, timetables of bus lines are coordinated with those of rail.

Figure 2: Regensdorf-Watt regional bus Network (zvv.ch)

2. Simultaneous arrival and departure of buses to the railway stations result in special land use requirements around the stations, one of which is the adequate land space for the bus stops.

In addition to buses and minibuses, private cars play an important role as rail feeders, too, especially in suburban areas, where walking and cycling distances to the stations exceed the acceptable norms. As a result, adequate parking facilities, including Park & Ride lots must be provided to fulfil the needs of those arriving by cars to the railway stations.

2.3 Potential benefits of autonomous vehicles

Besides the investments and investigations into the topic of autonomous vehicles as rail feeders by authorities, cities and public transport entities, researchers have also engaged themselves in studying the possibilities and assessing the benefits of applying such vehicles in the context of public transportation. The question of achievable benefits of using autonomous shared cars and autonomous buses as feeder services has not yet been answered completely in research, but through review of literature and the study of latest developments in this field, their plausible benefits can be formulated.

In general, there are three views on the interactions of public transportation and the autonomous shared vehicles. One is that the share of public transport ridership would increase, as the autonomous vehicles will serve as the last mile feeder to existing transport systems; second supports the cooperation of the two modes and their integration (Merlin, 2017) and the last opinion argues that the automated vehicles will cannibalize the public transport due to the direct competition. In this research, rather the first and second views are the topics of interest.

The most important benefit that can be achieved by using autonomous buses and minibuses as feeders to the rail would be the cost savings due to the elimination of driver factor. This saving in costs reduces the overall costs of running the feeders and such savings can be used to invest in more autonomous buses and minibuses (Sinner et al., 2017) and therefore to increase the coverage and frequency of feeders which again results in higher attractiveness of public transport systems in general and rail in a more specific sense. Brons et el. (2009) argue that improving and expanding access services to railway stations result in increased rail use. They discuss that less travel times to rail stations and increased frequency of feeder services improve the attractiveness of rail transport and result in higher modal share of rail.

Autonomous feeder systems would also increase the attractiveness of public transport systems in the sense of their added value and level of comfort, and therefore result in reduced amount of car ownership, which also reinforces the increase in public transport share. In a scenario where a passenger can hail an autonomous shared car via their smartphone or get on an autonomous bus, ride to the train station, continue their trip with the rail without the worrying of the hassle of finding a parking spot, the incentives to own a car are low.

Another positive outcome of applying autonomous shared cars as feeders for rail is the impact they have on the overall number of cars driving to the station and eventually, needing a space for full-day parking. The most important impact a shared system can have on land use and spatial needs would be the space savings due to the reduction of overall cars in the region, leading to less parking space needs and less congestion. There have been various studies in Europe and US to estimate what share of conventional cars could be replaced by ridesharing. The results vary from two thirds (Fulton et al., 2017) to 90% (International Transport Forum, 2016). In general, point to point and free-floating car sharing and ridesharing systems lead to reduced ownership of private cars, which lies between 5 to 15 private cars for one additional shared car added to the fleet (Transport & Environment, 2017). This argument intensifies, considering the fact that shared autonomous vehicles can drop-off the passengers at the station and continue to pick up next group of people from their origins. Additionally, private autonomous vehicles have the ability to return home or become available to another family member in the household, without the need to park and wait for its owner at the station. Less autonomous vehicles are required to serve the same number of people, compared to a situation where they arrive with private cars, therefore the need for full-day parking spaces at and around the stations will decrease.

Although the spatial need for parking space and Park & Ride facilities might decrease in case of the automation of the feeders, on the other hand the space needs for drop-off areas of AVs may increase, as all the vehicles would arrive and depart at the same time according to the railway timetable. The space needed for bus stops may increase or decrease according to the size of the buses, density of bus network and the proportion of shared autonomous vehicle; that means the share of passengers that would shift from today's bus feeder systems to autonomous shared cars and minibuses.

3 Research Structure

3.1 Overall Research Question

The emergence of autonomous driving will potentially reshape the available options for designing feeder services to railway stations. Private cars and buses will not only be gradually automated, but in-between public and private transport a possible third entity (shared autonomous cars) could also appear. Table 1 summarizes the key features of the three systems.

Table 1: Features of feeder systems

	Autonomous private cars	3rd entity (Shared autonomous cars)	Autonomous public transportation
Characteristics and parameters	- 24-hour availability - No spatial constraint - No temporal constraint	- 24- hour availability - Dynamic routing - Dynamic stops - Elimination of driver	- Fixed route - Fixed stops - Fixed schedule - cost saving due to the elimination of driver
Ownership	Private	Company	Company
Spatial Bundling	No	Possible, but not needed	Yes
Temporal Bundling	No	No	Yes

Today's design and location of railway stations are determined by the features of currently available systems: private cars for P+R as well as buses in line-based public transportation. With the emergence of a third entity and the transformation of the existing ones, the requirements in terms of station design and location are potentially subject to change. This research project aims at investigating those along the lines of the subsequent overall research question:

> **What are the optimal number, location and design of railway stations along lines in commuting zones of agglomerations in a transport system with autonomous cars, shared feeder services and buses? Which will be the requirements given by land use and consequences for the latter?**

3.2 Subsidiary Research Questions

From the main research question, the following subsidiary questions can be derived:

1. **Which are the micro-level space requirements for a railway station to work as an interchange between a feeder service and railway in terms of road accessibility, space for drop-off and boarding, space for parking, etc.?**

   This question is motivated by the implicit temporal bundling of demand through the train arrivals and departures. Unlike in origin to final destination traffic, demand is not equally

distributed over time, but displays high peaks before the scheduled train departures and after the arrivals of the latter. The capacity of the interchange facilities, such as the space for boarding buses or autonomous shared cars, will be utilized to the maximum during a short laps of time. In return, the available space can be limiting to the total throughput of the system. The critical elements to the system shall be identified and quantified.

This subsidiary question will be addressed in chapter 4.

2. What are the achievable benefits by using autonomous shared cars and autonomous buses as feeder services compared to the status quo?

In this part, we analyse what benefits a pure replacement of the feeder services by autonomous vehicles (of whatever size) can bring. The location of railway stations remains unchanged.

The results to this question (in chapter 6.1) serve as reference for questions 3 and 4.

3. What are the benefits in terms of travel time, if railway stations are relocated? Which implications would such a relocation have on urban planning? Is a relocation advisable from the urban planning perspective?

Historically railway stations have been located, whenever possible, in centres of agglomerations, with development and housing areas defined by walking distances. This historic pattern still exists, although the stations might not be located in the right location to meet today's public and private transport requirements. With the automation of road transport, the possibilities offered by feeder services will change once more.

This question aims at checking whether today's locations are suitable for future feeder services. Furthermore, one needs to check whether the optimal station from the transport system perspective is the same for all feeder services or whether different feeder services (shared autonomous cars vs. autonomous buses) would require different locations. In other words, is the optimal location robust with respect to a change of feeder system?

On the other hand, from the transport systems' point of view, it might be feasible to move a station to another location, but this may contradict with urban planning principles.

4. What are the benefits in terms of travel time, if the station density along a railway line decreases (i.e. one or more stops can be omitted)? Which implications does it have on urban planning?

If the number of stations decreases, customers now enjoying direct access to a railway station will have to take a feeder service first. On the other hand, average speed of railway services increases. This question aims at addressing the trade-off between access time to the rail on the one hand and speed on the rail on the other hand.

The work on questions 2 to 4 involves two parts: a theoretical one and an applied one. In the first part, the dominant influential factors will be identified through theoretical test cases (Tirachini et al., 2010) (see chapters 5 and 6). The second part consists of three cases which have been fixed in agreement with SBB. They are addressed in chapter 8.

4   Q1: Spatial requirements for a station

This chapter deals with the spatial requirements of a railway station to serve as an interchange hub for one of the three possible feeder services: autonomous private cars, autonomous buses or shared on-demand cars (3rd entity).

> **At the railway station, a temporally discrete transport system which bundles traffic (the railway, "Pendelsystem") thus meets up with a temporally continuous system (a feeder system based on private or shared cars, "Stetigförderer").**

This link is particularly challenging from the design perspective, since a large number of cars will arrive in a very short time laps before the scheduled train departure. Unless service frequency on the rail side is very high (interval less than 5 – 8 minutes), passengers' arrival at the station is targeted to one specific scheduled train departure (Weidmann & Lüthi, 2006). This mechanism can be expected not to change fundamentally with autonomous feeders. Thanks to real-time information being available (e.g. via smartphone apps), one rather needs to expect a further concentration of passengers' desired arrival just before the train departure. Hence the station facility needs to be designed in a way that in can cope with such a high peak influx. The load on the feeder and thus the road network is not continuous in time, but has a few very high peaks.
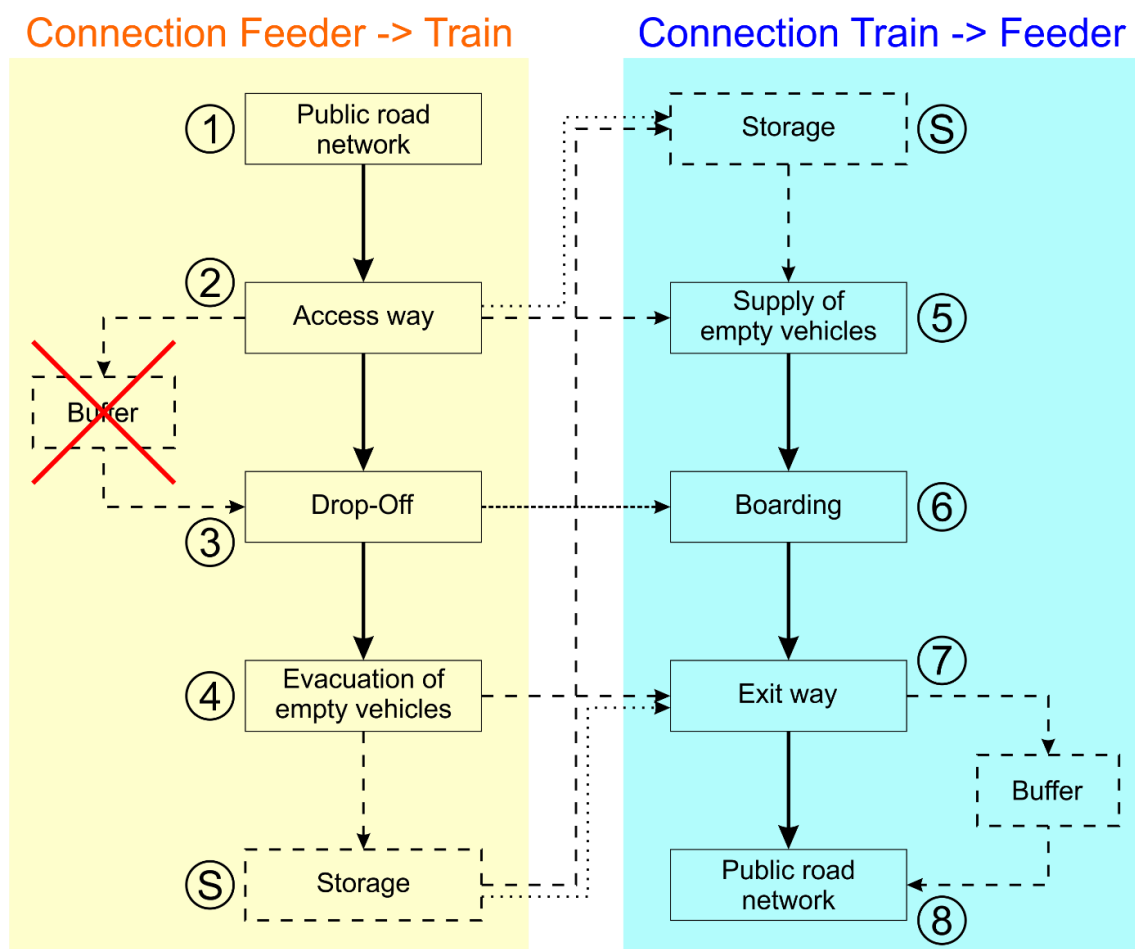
Figure 3: Flow chart of connections feeder-train and vice versa

The connection from feeder service (regardless of its exact nature) to train involves the following steps (Figure 3 left column):

1. the trip on the public road network,

2. the access way to the station drop-off facility,

3. the drop-off process itself,

4. the evacuation of the empty vehicles to either the storage facility or the exit way (and the public road network) to pick up the next passenger(s).

Similarly, the opposite connection from train to feeder service involves the subsequent steps (Figure 3 right column):

5. sufficient supply of empty vehicles from either a storage facility or directly from the access way (and the public road network),

6. the boarding process itself,

7. the exit way leading from the boarding facility to the public road network,

8. the trip on the public road network.

In some cases, the direct passage of vehicles from drop-off (step 3) to boarding (step 6) is possible. However, given the strongly asymmetric nature of traffic streams (in the morning oriented to the railway station, in the afternoon in the opposite direction) with only little demand travelling against the load direction, the occurrence of this direct passage is not very frequent. We therefore neglect it for the subsequent considerations.

4.1 Capacity requirements

In order to avoid spillbacks in the system, the capacity of the downstream step generally needs to be greater or equal than the maximal output of the immediately upstream step. In some cases, a buffer can be included, which then allows coping with a lower capacity downstream.

4.1.1 Drop-off of passengers

We first analyse the capacity requirements of the drop-off process (from the most upstream to the most downstream step) when vehicles with passengers arrive shortly before the scheduled train departure (Figure 3 left column).

4.1.1.1 Public road network

We assume that **the street leading to the railway station has one lane per direction**. In this case, the maximum possible throughput is the saturation flow μ. With conventional vehicles, $\mu \cong 1'800\ veh/h$. With automation, shorter reaction times and shorter standstill distances (Ambühl et al., 2016) allow an increase of the saturation flow. According to Sinner & Weidmann (2017), the saturation flow of autonomous cars (length ca. 5 m) $\mu \cong 2'600\ veh/h$. When

comparing to other values in literature (see for instance Friedrich (2015) or Tientrakool (2011)), $2'600\ veh/h$ is rather at the conservative end of the scale. Reductions of the saturation flow due to the road geometry (e.g. right or left turns, see Transportation Research Board (2010) or Sinner (2015)) are neglected at this stage. They depend on the concrete geometric design of the facility in the particular setting. In this project, the targeted level of detail permits to neglect these reductions, but they would need to be considered in the detail planning of the respective facility.

4.1.1.2 Access way

By providing **an access way that has as many lanes as the road leading to the station,** it can be guaranteed that the arriving cars are evacuated without the formation of a queue. A buffer is thus not necessary, and secondly, its inclusion would have negative effects on the reliability of the connection feeder-train: the existence of a buffer would mean that some cars are stalled for some time until they could access the station to drop-off their passenger(s). These passengers might thus miss their connection.

4.1.1.3 Drop-off area

For the reason outlined above (reliability of the connection feeder-train), there shall be no buffer before the drop-off area (see Figure 3). Hence, the throughput of the drop-off area needs to be at least as high as the one of the access way which is again equal to the maximum arrival rate given by the public road network, i.e. as high as $\mu = 2'600\ veh/h$. The corresponding minimal headway is $t_{H,min,access} = \frac{1}{\mu} = 1.38\ s$.

On the level of the single drop-off bay, the headway, can be calculated as follows after Sinner & Weidmann (2017):

$$t_{H,min,bay} = t_d + \frac{v}{a} + \frac{1}{\mu} \tag{1}$$

Where t_d is the dwell time and $\frac{v}{a}$ a term to account for the time losses due to deceleration and reacceleration. With $t_d = 30\ s$, $v = 6.45\ m/s = 23.2\ km/h$ and $a = 1.5\ m/s^2$ (Sinner & Weidmann, 2017), we obtain $t_{H,min,bay} = 35.7\ s$. This value matches well with the order of magnitude found by Lutz (2017).

Dividing the headway of the single bay by the one of the access way, we obtain the required number of bays $m_{required}$ which is always less or equal than the effective number of bays m:

$$m \geq m_{required} = \frac{t_{H,min,bay}}{t_{H,min,access}} = 25.9\ bays \tag{2}$$

The drop-off area thus needs to consist of at least 26 bays in order to be sure to able to receive the maximal flow of 2'600 veh/h even if for a only short time period of time (e.g. one or two minutes). This number may only be reduced if we can make sure, the arrival flow on the public road network is always lower than the saturation flow of $\mu = 2'600\ veh/h$.

Different designs of the drop-off area are conceivable to accommodate these bays.

4.1.1.3.1 Layout 1

The **simplest design would be a single lane of drop-off bays with a passing lane next to it** (Figure 4). The bays are filled from the front to the rear as indicated in Figure 4. If the number of bays is sufficient (i.e. higher than the above calculated number), the first cars will have cleared their respective bay before the line has been entirely filled. The front bays can thus be refilled. However, as clearing of bays has necessarily further progressed backwards than re-filling (because a bay cannot be reused before it has been cleared), the streams of leaving vehicles (show by the blue arrow) and entering vehicles (shown by the orange arrow), each at a saturation flow of up to $\mu = 2'600\ veh/h$ (we assume stationary conditions over time), do superpose each other. On this small section of lane, the combined flow would thus be $2 \cdot \mu$ which is obviously not possible.
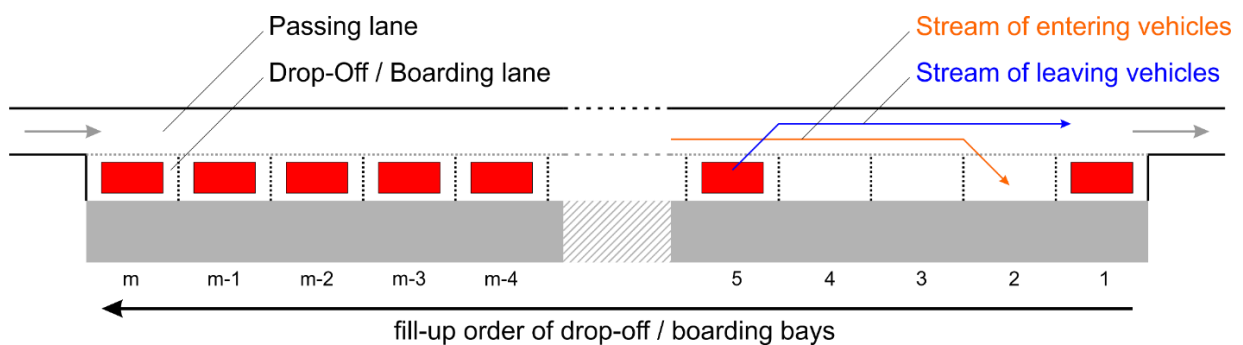
Figure 4: Design of drop-off area with a single lane of bays and a passing lane
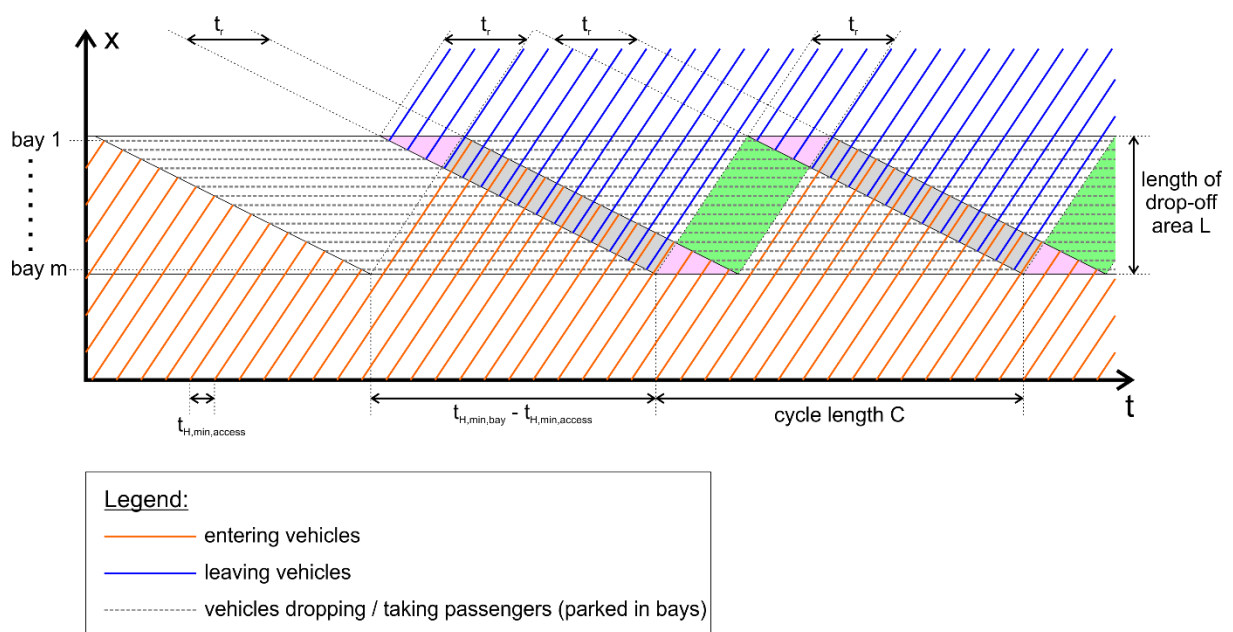
Figure 5: Time-space-diagram of drop-off facility

This fact can be proven be considering the time-space-diagram of the drop-off facility shown in Figure 5. The cycle time C is the time span between two consecutive usages of the same bay:

$$C = m \cdot t_{H,min,access} \tag{3}$$

With m being the number of bays. Furthermore $C \geq t_{H,min,bay} \Leftrightarrow m \geq \frac{t_{H,min,bay}}{t_{H,min,access}}$ which is the same as equation (2). $t_{H,min,bay} - t_{H,min,access}$ is the time-loss of a single vehicle due to its stop. It corresponds to the dwell-time plus the time-loss through deceleration and acceleration:

$$t_{H,min,bay} - t_{H,min,access} = t_d + \frac{v}{a} \tag{4}$$

The time laps t_r between the moment when a vehicle is leaving its bay and the next vehicle occupying the same bay is thus given by:

$$t_r = C - \left(t_{H,min,bay} - t_{H,min,access}\right)$$

$$\Leftrightarrow t_r = C - t_{H,min,bay} + t_{H,min,access} \tag{5}$$

$$\Leftrightarrow t_r = (m+1) \cdot t_{H,min,access} - t_{H,min,bay}$$

With the $C \geq t_{H,min,bay}$, we obtain $t_r \geq t_{H,min,access}$.

In Figure 5, we can see that the stream of the entering vehicles (shown in orange) and the one of the leaving vehicles (shown in blue) do superpose each other in the grey-shaded area. This confirms the finding of Figure 4. In return, there is no flow in the green-shaded area.

One can mathematically prove that the **average flow q_{mean} over one entire cycle C and the entire length L of the drop-off is always equal to $q = \frac{1}{t_{H,min,access}}$**:

$$q_{mean} = \frac{q \cdot C \cdot L + (2q - q) \cdot A_{grey} + (0 - q) \cdot A_{green}}{C \cdot L}$$

$$\Leftrightarrow q_{mean} = \frac{q}{C \cdot L} \cdot \left(C \cdot L + A_{grey} - A_{green}\right) \tag{6}$$

Considering that

$$A_{grey} + 2 \cdot A_{pink} = t_r \cdot L = A_{green} + 2 \cdot A_{pink}$$

$$\Leftrightarrow A_{grey} = A_{green} \tag{7}$$

Equation (6) thus yields $q_{mean} = q$.

q.e.d.

Filling up the bays in the other order (from rear to front instead of from front to rear) does not change the fundamental results (see Figure 6). There remains an area where the flow doubles (grey-shaded area) and another one of equal size where the flow is 0 (green-shaded area). Proving that both areas have the same size works fully analogously to equation (7).
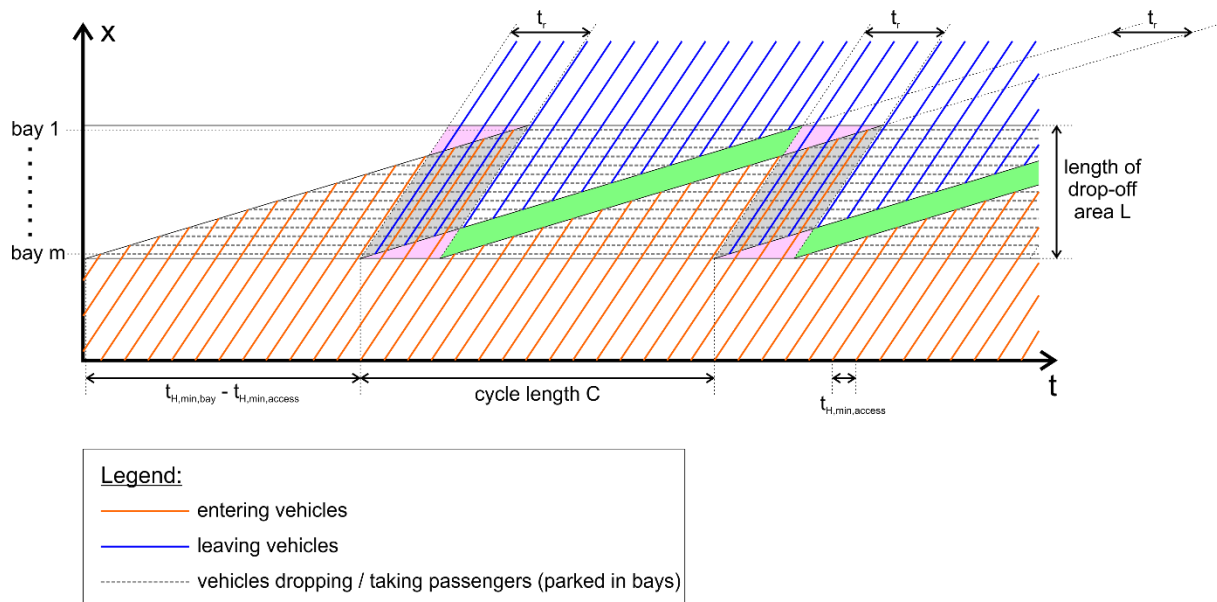
Figure 6: Variation of time-space-diagram for drop-off / boarding facility

The proposed design in Figure 4 is thus only possible if either of the following conditions is fulfilled:

- No refill of the bays is required, i.e. the number of bays is higher than the total number of cars arriving before the departure of the most demanded departing train. In this case, one could then even renounce at the passing lane.

- The flow of arriving vehicles is always lower than $\frac{\mu}{2}$ such that the combined superposed flow of the entering and the leaving flow remains below μ.

4.1.1.3.2 Layout 2

In order to solve the issue of the superposition of saturation flows, the drop-off lanes and the passing lanes can be doubled as shown in Figure 7. Bays can be filled in an alternating way as illustrated in Figure 7. Hence the streams of entering and leaving vehicles in each passing lane are only $\frac{\mu}{2}$ such that their superposition does not exceed the saturation flow μ. For this layout, the total number of bays is the first **even** integer number greater than $\frac{t_{H,min,bay}}{t_{H,min,access}} = 25.9 \ bays$, which yields in this case the same number of bays as in layout 1. The required length of this design would only be half of the one in Figure 4, while the required width would be double. One shall note that this layout requires very precise operation of the cars since the entering and leaving flows need to perfectly imbricate into each other. With this layout of the drop-off area, it is very difficult to guarantee a stable operation, as the slightest disturbance brings the system out its equilibrium.
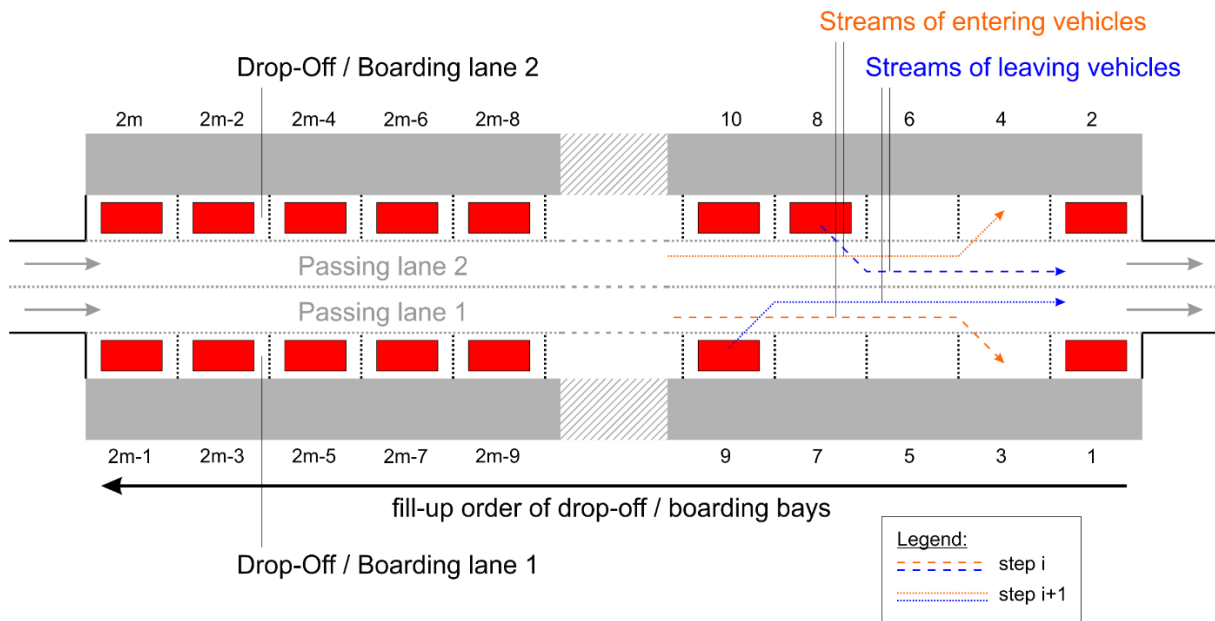
Figure 7: Design of drop-off area with two lanes of bays and two passing lanes

4.1.1.3.3 Layout 3

Alternatively, a design with n parallel rows of m bays each (without passing lanes) can be chosen (Figure 8).
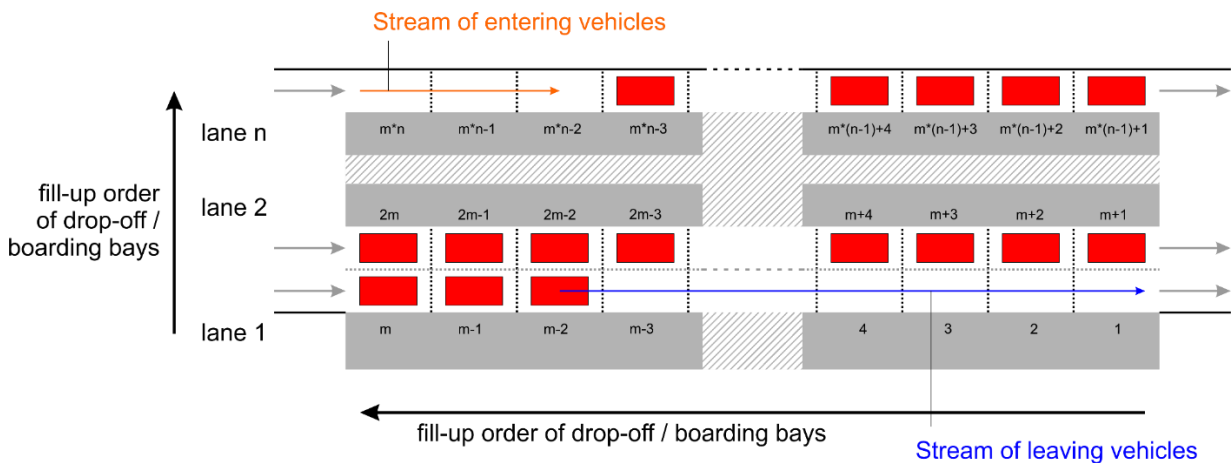
Figure 8: Design of drop-off area with multiple lanes of bays without passing lanes.

Two design conditions need to be fulfilled for such a layout to work in practice:

- The total number of bays $n \cdot m$ needs to be higher than the required number of bays (e.g. 26 in our case).

- The last vehicle in a given lane needs to have cleared its place before the first vehicle of the next round for the same lane arrives. This condition can be translated mathematically to read as follows (Sinner & Weidmann, 2017):

$$t_{H,min,m \cdot n\ bays} \cdot (n \cdot m - m + 1) \geq t_{H,min,bay} \tag{8}$$

The headway of the total drop-off area $t_{H,min,m \cdot n\ bays}$ is equal to $t_{H,min,access} = \frac{1}{\mu} = 1.38\ s$, whilst the headway of the single bay is equal to $t_{H,min,bay} = t_d + \frac{v}{a} + \frac{1}{\mu} = 35.7\ s$. Hence,

$$n \cdot m - m = m \cdot (n - 1) \geq \left(t_d + \frac{v}{a}\right) \cdot \mu = 24.8 \tag{9}$$

We are thus looking for a combination of integer values n and m which satisfies inequality (9). Some possible combinations in this case are:

- $m = 2$ and $n = 14$ ➜ 28 bays
- $m = 3$ and $n = 10$ ➜ 30 bays
- $m = 4$ and $n = 8$ ➜ 32 bays
- $m = 5$ and $n = 6$ ➜ 30 bays
- $m = 7$ and $n = 5$ ➜ 35 bays
- $m = 9$ and $n = 4$ ➜ 36 bays
- $m = 13$ and $n = 3$ ➜ 39 bays

The choice of the most suitable combination needs to be made in the light of the spatial conditions in the particular case. A high value of n generally leads to a smaller number of bays and thus also to less required surface. However, the number of platforms and subsequently the number of access stairs grows. Reversely, a high value of m has the advantage that less platforms are needed.

It shall be stressed that **no pedestrian streams are permitted to cross the lanes of the cars** as this would necessarily lead to a reduction of the possible flow and thus cause spill-backs. **The pedestrian access and egress to/from the platforms thus needs to be assured via an under- or over-pass.**

4.1.1.4   Evacuation of empty vehicles from drop-off area

The lane evacuating the empty vehicles from the drop-off area should have the same capacity as the access way, hence one lane is sufficient under the assumption that the road access has only one lane, too.

4.1.2 Boarding of passengers

We now analyse the boarding process from the most upstream to the most downstream step. In this case, the connection has already been made. The inclusion of buffers or small waiting times for passengers is thus permitted.

4.1.2.1 Supply of empty vehicles & boarding area

The supply of the empty vehicles is the most upstream process step which can dictate the throughput of all other steps further downstream. Assuming that the drop-off area will used for boarding as well, it follows that the supply rate of empty vehicles should be the same as the capacity of the access way to the drop-off area, i.e. $\mu = 2'600 \, veh/h$ which corresponds to one lane. This allows for an efficient use of the facilities that are needed anyways for drop-off.

4.1.2.2 Exit way

The throughput of the boarding area being $\mu = 2'600 \, veh/h$, the exit way needs to have the same capacity in order to avoid spill-backs into the boarding area. With one lane, this condition can be satisfied.

4.1.2.3 Public road network

The passage from the exit way to the public road network is critical, as we cannot predict the flow of vehicles the road is able to take. In order to avoid spill-backs into the exit way from the boarding area and thus eventually also to the latter itself, a buffer is required over here (Figure 3 right column). The number of vehicles the buffer needs to accommodate (N_{buffer}) depends on the one hand on the accepted flow by the receiving road network $q_{road\ network}$ and on the other hand on the total number of vehicles N_{tot} leaving the station facility after the arrival of the design load train:

$$N_{buffer} = (\mu - q_{road\ network}) \cdot \frac{N_{tot}}{\mu} \tag{10}$$

Where $\frac{N_{tot}}{\mu}$ corresponds to the total time span during vehicles are boarded.

4.2 Schematic design of a station

Figure 9 shows a sample design of a station facility. The drop-off and boarding area can be designed according to one of the previously explained layouts by taking into account their respective limitations.

The exact design of the storage facility depends on several aspects:

- How many cars need to be stored there while waiting to pick up passengers arriving on the next train? The total number of passengers is the main input in this context.

- Are cars shared or private? While shared cars can be assumed to be all identical, private cars are not. For the latter, a very specific car parked in the middle of the storage area might be requested to leave before the surrounding ones do. This cannot occur with shared cars which leave the storage on a strict First-In-First-Out basis (FIFO).
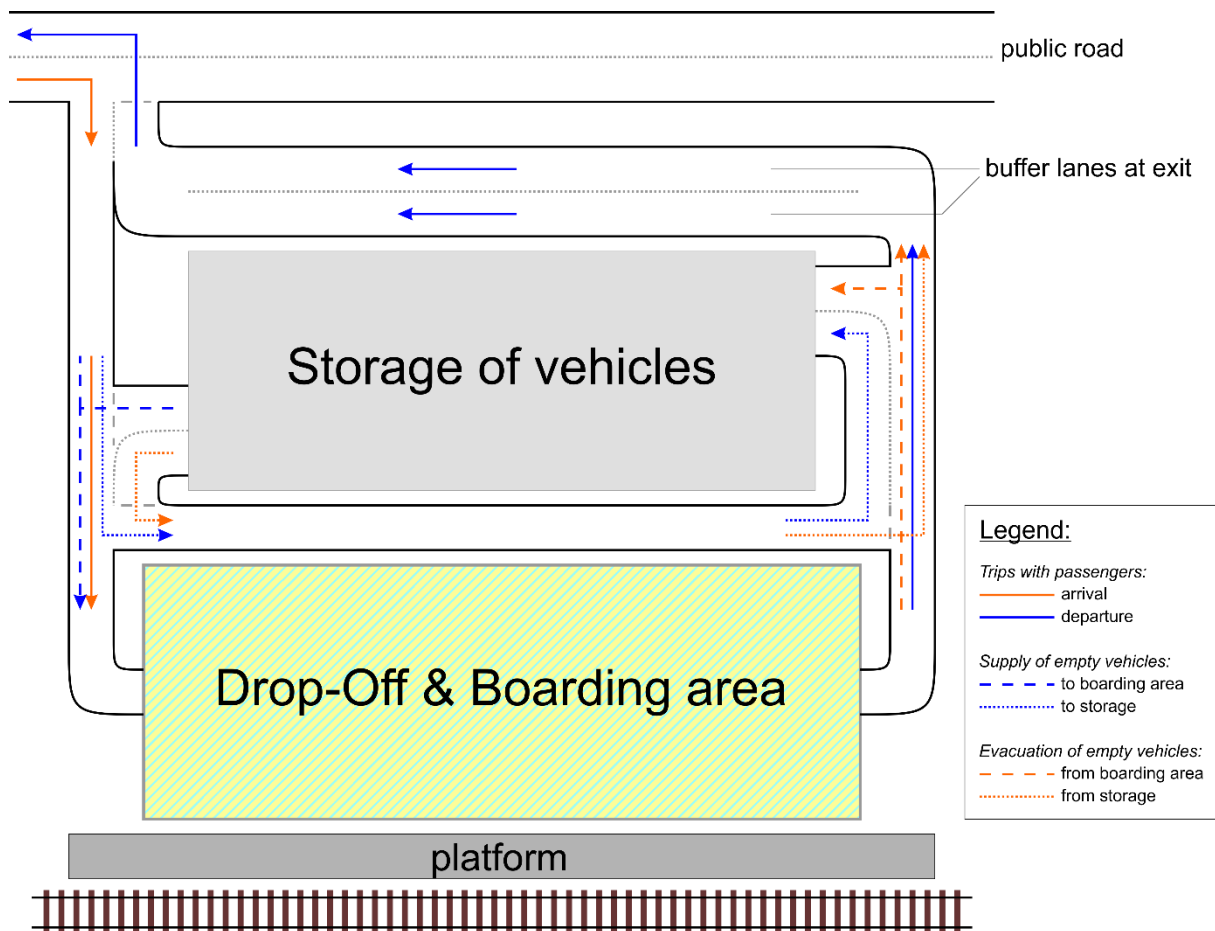
Figure 9: Sample design of a station

In both cases, the parking facility can be designed in a much more efficient way than today, as autonomous cars can manoeuver more precisely and no passenger is required to access the car whilst being parked. Alessandrini et al. (2015) and Nourinejad et al. (2018) have proposed different designs of parking facilities for shared or private autonomous cars respectively.

When translating the previous findings in terms of car capacity into numbers of passengers, we need to assume an average occupancy rate. According to Lutz (2017), an average occupancy of **1.6 passengers per car** can be assumed. This value corresponds to today's average occupancy in Switzerland, as the findings by the European Environment Agency (2010) show. If we further assume that **all passengers would like to arrive within a time interval of 5 minutes before the scheduled train departure**, the number of cars that can arrive during that time is maximum 217 vehicles. This **yields us an absolute maximum of 347 passengers per train**. One should bear in mind, that this is a non-conservative calculation which assumes that one lane of the public road network is only used to supply cars to the railway station. Not a single other car would be permitted during that 5 minutes period.

Assuming a longer arrival period does not yield a smaller the drop-off area. Figure 10 shows a qualitative representation of the temporal distribution of the arrival flow (the form of the curve does not have a specific meaning): on the left with an assumed arrival period of 5 minutes, on the right with an assumed arrival period of 10 minutes. The area below both blue curves is the same (i.e. the same number of passengers arriving). With a doubled arrival

period, the average flow is obviously cut by half. However, the maximum flow, which matters for the design of the drop-off facility, does not change. **The reduction of the size of the drop-off area as a consequence of a doubled arrival period latter would only be possible, if there were a mechanism in the system that could guarantee that the arrivals do effectively spread out constantly over the entire period.** As long as such a mechanism does not exist, short but intense peaks of the arrival flow are possible and the drop-off area needs to be designed to accommodate those.
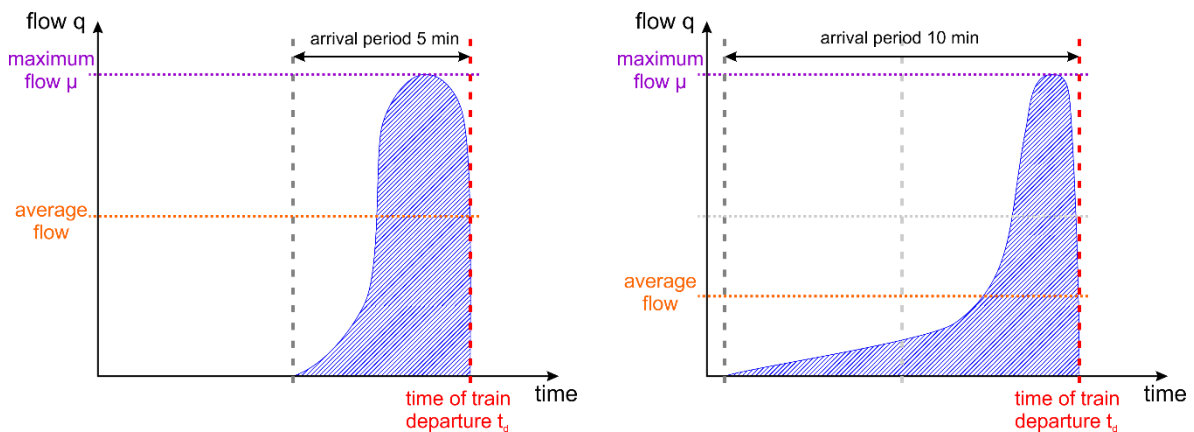
Figure 10: Extension of assumed arrival period

Similarly, Figure 11 depicts the effect of a reduction of the number of passengers (materialized by the area below the blue curves, respectively by the average flow). If the latter is cut by 50%, this does not automatically yield a smaller maximum flow. The reduction of the number of passengers merely results in a more pronounced concentration of the arrivals in the last minutes before the train departure.
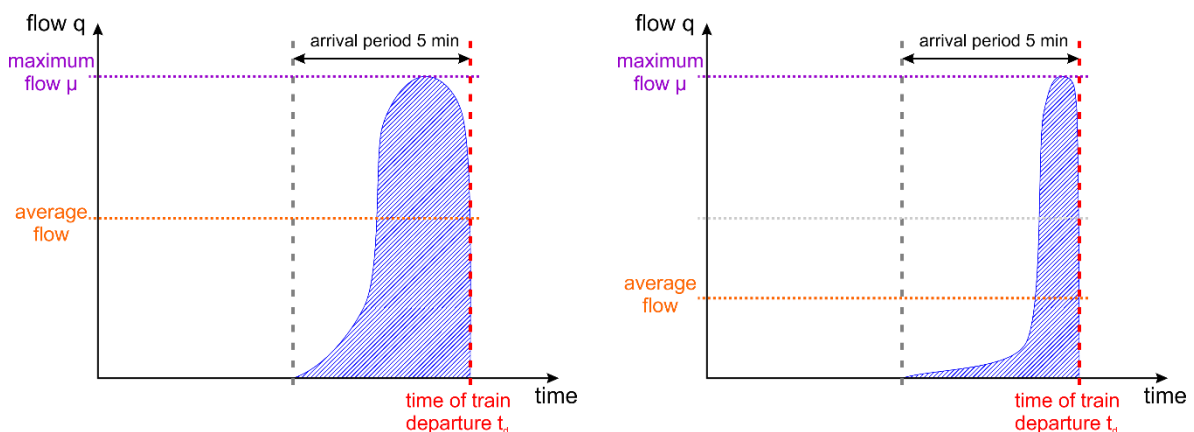
Figure 11: Reduction of number of passengers

Hence, as long as we do not have any further information on the exact temporal distribution of vehicle arrivals, the size of the drop-off are is not determined by the total number of passengers, but by the maximum possible inflow from the road network (see section 4.3.2.3 below).

4.3 Spatial requirements

4.3.1 Drop-off & boarding area

The size of the drop-off and boarding area depends on the chosen layout. For each of them, we depart from the following assumptions:

- Width of drop-off and boarding lane, as well as passing lane: 3 m

- Length of bay: 5 m

- Platform width:

  o Single-sided platform: 3 m

  o Doubled-sided platform: 6 m

  o This width may seem high at the first glance, but we have to consider that all cars arrive at the same time (thus creating high pedestrian traffic) and that a part of this width is made unusable by the opening doors of the cars.

- Flow to be accommodated: $\mu = 2'600 \ veh/h$

  o Required minimum number of bays: 26

4.3.1.1 Layout 1: a single drop-off/boarding and passing lane

- **Width** = 2 lanes + one-side platform = 2 * 3 m + 3 m **= 9 m**

- **Length** = 26 bays * 5 m **= 130 m**

- **Space for turns at end of lane: at least 3m of additional length at each end**

- **Area: 9 * (130 + 6) = 1224 m²**

4.3.1.2 Layout 2: two drop-off/boarding and passing lanes

- **Width** = 4 lanes + 2 one-side platforms = 4 * 3 m + 2 * 3 m **= 18 m**

- **Length** = 13 bays * 5 m **= 65 m**

- **Space for turns at end of lane: at least 3m of additional length at each end**

- **Area: 18 * (65 + 6)= 1278 m²**

4.3.1.3 Layout 3: multiple parallel drop-off lanes without passing lanes

The final size depends on the chosen combination of the number of lanes n with m bays each. A **collecting lane plus turning space** needs to be included at each end of the facility in order to distribute/collect the car streams to/from the different drop-off/boarding lanes. In sum, 6 m are needed once for each end. The dimensions of possible combinations are given in Table 2.

Table 2: Dimensions of station layout 3

Combination	n	m	Width	Length	Area
1	14	2	84 m	10 m + 12 m	1848 m²
2	10	3	60 m	15 m + 12 m	1620 m²
3	8	4	48 m	20 m + 12 m	1536 m²
4	6	5	36 m	25 m + 12 m	1332 m²
5	5	7	30 m	35 m + 12 m	1410 m²
6	4	9	24 m	45 m + 12 m	1368 m²
7	3	13	18 m	65 m + 12 m	1386 m²

Layout 1 is the most space efficient option but it cannot be used if the total vehicle demand exceeds the total number of bays. Layout 2 is a little more space-efficient than layout 3, but features strong disadvantages in terms of robustness. Layout 3 with the combination $n = 6$ and $m = 5$ is almost as space-efficient as layout 2 (1332 m² versus 1278 m²), but does not have the same weaknesses when it comes to stable operation.

4.3.2 Storage area

The spatial need depends on the type of autonomous vehicles: shared or private.

4.3.2.1   Shared vehicles

Let N_{tot} be the total number of vehicles waiting to pick-up passengers from the most heavily used train in the day. The area of the storage facility is thus roughly:

$$A \cong N_{tot} \cdot 2.5\,m \cdot 5\,m = N_{tot} \cdot 12.5\,m^2 \tag{11}$$

It has been assumed implicitly that vehicles may not wait inside the boarding area, as this might block the latter for arriving vehicles dropping passengers taking the immediately arriving train. The shape of the storage area does not matter, as all vehicles are identical and the storage facility is operated on a FIFO-basis.

4.3.2.2   Private vehicles

The space required for a storage facility of private vehicles is certainly larger than for shared vehicles. Additional gap lanes need to be included in order to allow for manoeuvring when exiting a vehicle parked in the middle of a parking island. Nourinejad et al. (2018) have proposed different designs as well as a methodology to choose the optimal one based on the available space as well as the demand for parking sports by taking into account the required relocation manoeuvers inside the parking facility.

4.3.2.3   Multiple road access

If multiple roads lead to the railway station, they can either be merged into one main access road before entering the station premises or they can be kept separate.

The former option has the advantage that the merger acts as a dosage facility with the maximum flow entering the station being limited to the saturation flow of one lane. In return, congestion can happen with spill-backs to main arterial roads where other traffic is blocked. Furthermore, the connection feeder-train is endangered when vehicles are trapped in congestion.

The option with multiple roads and lanes leading to the railway station premises has the advantage that passengers experience less congestion. But the area of the drop-off facility needs to be multiplied accordingly in order to cope with potentially much higher influx of vehicles. The area of the storage facility is not affected, as it is designed based on the total number of vehicles and not on the maximum momentary flow.

4.4   Autonomous Ridesharing

The main difference between autonomous shared cars and autonomous ridesharing using minibuses lies in the load factor which is higher. In return, the saturation flow drops as vehicles are larger (Sinner & Weidmann, 2017) and the dwell times might be higher. The methodology to calculate the required number of bays and the required land surface stays exactly identical to the previously outlined calculations for autonomous cars.

4.5   Autonomous buses

When considering a feeder with autonomous buses (operating on fixed lines), the main difference lies in the fact that – in contrary to on-demand car-sharing or ridesharing – we have a planned system where the number of vehicles and their arrival times are exactly known in advance. The interchange facility can thus be exactly tailored to that specific number without be obliged to provide a facility designed for the maximum possible influx.

5 Methodology (Q2-Q4)

This chapter outlines the methodology used for the generic test cases assessing the effects of different variables on the **optimal location of a railway station**. Later on, the model is applied in the case studies to real situations.

All calculations are based on the following basic setting: there is a town where a railway line (black line in Figure 12) passes through (or nearby in other cases). The main demand relation (oriented towards a major centre) is always to the left (negative x on the horizontal axis, see Figure 12). The railway station (materialized by the red dot) moves along the railway line. Different statistics describing the performance of the feeder systems (travel times to station, ridership potential) are calculated for each location of the station.

> **Here, the optimal location of the railway station of a given town is defined as being the location which minimizes door-to-door travel times in the main origin-destination pair, averaged over the entire town weighted by settlement densities.**

Main origin-destination pair
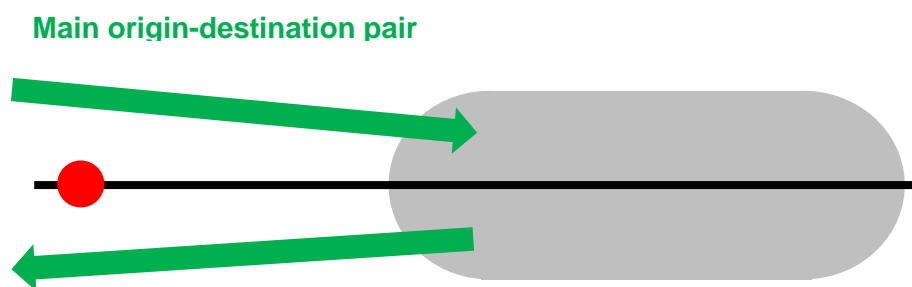
Figure 12: Generic town with main origin-destination pair

5.1 Description of the generic towns

This section describes the parameters of the built environment which enter into the calculation of the generic test cases.

5.1.1 Form of the town

Three different forms of town are considered (see Table 3): circular, parallel to the railway line and perpendicular to the railway line. The coordinate axes are always defined such that the town is centred in both planar directions at the origin.

5.1.2 Position of the railway line

Similarly, we consider three different possible positions of the railway line relative to the town (see Table 4): centrally through the town, tangential to the latter as well as fully outlier.

Table 3: Considered town forms
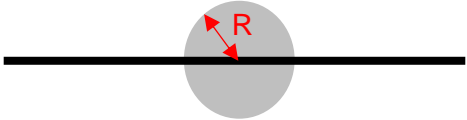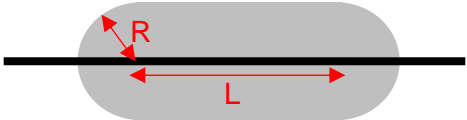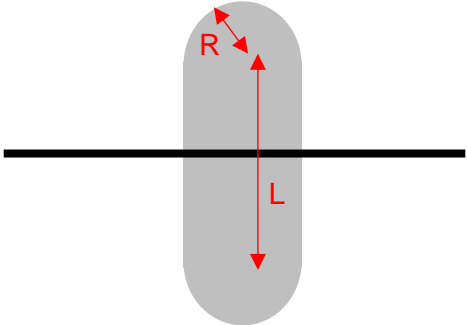
Circular town	
Town parallel to railway line	
Town perpendicular to railway line	

Table 4: Considered positions of the railway relative to town

Central	
Tangential	
Outlier	

5.1.3 Size of the town

We consider three different town sizes: small, medium and large. Their dimensions depending on the form are given in Table 5. They were chosen such that they can capture the full diversity of towns in the area of interest of the present research: towns in residential areas in and around the Swiss agglomerations. Big cities like Zurich or Berne are explicitly not in the scope of this project. The domain of interest is the interval on the horizontal x-axis where the railway station varies in.

Table 5: Dimensions of generic towns

Form \ Size	Small	Medium	Large	Domain of interest for station location
Circle	R = 0,5 km L = -	R = 1 km L = -	R = 2 km L = -	[- 5 * R ; R]
Parallel	R = 0,5 km L = 4 * R	R = 1 km L = 3 * R	R = 2 km L = 2 * R	[- 5 * R – L/2 ; R + L/2]
Perpendicular	R = 0,5 km L = 4 * R	R = 1 km L = 3 * R	R = 2 km L = 2 * R	[- 10 * R ; R]

5.1.4 Settlement density distribution

Two different settlement density distributions are considered:

- Homogeneous with a density of 2000 inhabitants/km^2 all over the settlement area;

- Inhomogeneous with higher density in the middle of town (3000 inhabitants/km^2) linearly decreasing to lower density at the edges of the town (1000 inhabitants/km^2);

- When applying the model in the case studies, empiric density data can be used.

5.2 Description of the feeder systems

5.2.1 Car

From a travel time point of view, it does not matter whether the cars run autonomously or manually driven, respectively whether they are privately owned or shared. The cars provide the geographically most direct connections between a given point in the settlement area and the railway station (Figure 13). They take the shortest route provided by the road network and they do not have any intermediate stops to let other passenger board or alight. Cars can thus be considered as a **spatially continuous mode of transport**.
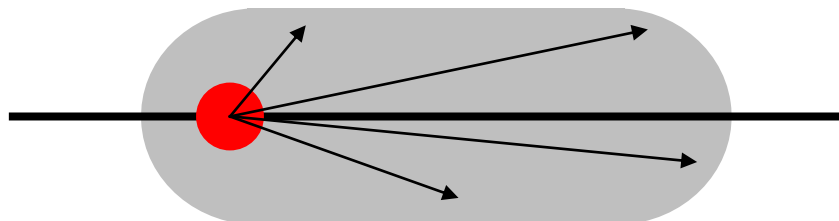
Figure 13: Car feeder system

5.2.2 Bus

In contrast to a car-based feeder system, the bus is line-based. It is thus a **spatially discrete mode of transport** which runs on given routes (Figure 14) and has intermediate stops to let passengers board or alight. Automation does not have an influence on the speed of the feeder system. However, thanks to the elimination of the driver, it becomes economically viable to run more lines and thus to partially reduce spatial bundling.
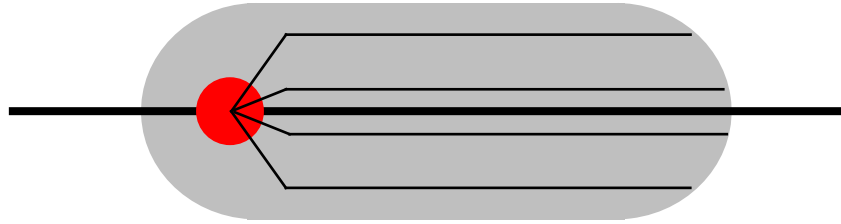
Figure 14: Bus feeder system

5.3 **Model**

5.3.1 Fundamentals

The basic concept of the model is identical to both feeder systems (Figure 15). The travel time gain experienced by any point in the settlement area through a relocation of the railway station can be expressed as follows:

$$\Delta t_P = TT_{rail}\, S_i S_0 + TT_{feeder}\, S_0 P - TT_{feeder}\, S_i P \qquad (12)$$

Since a differential computation is made, we needed to define a reference point, which in this case is a railway station located at the centre (x-axis-wise) of the town.
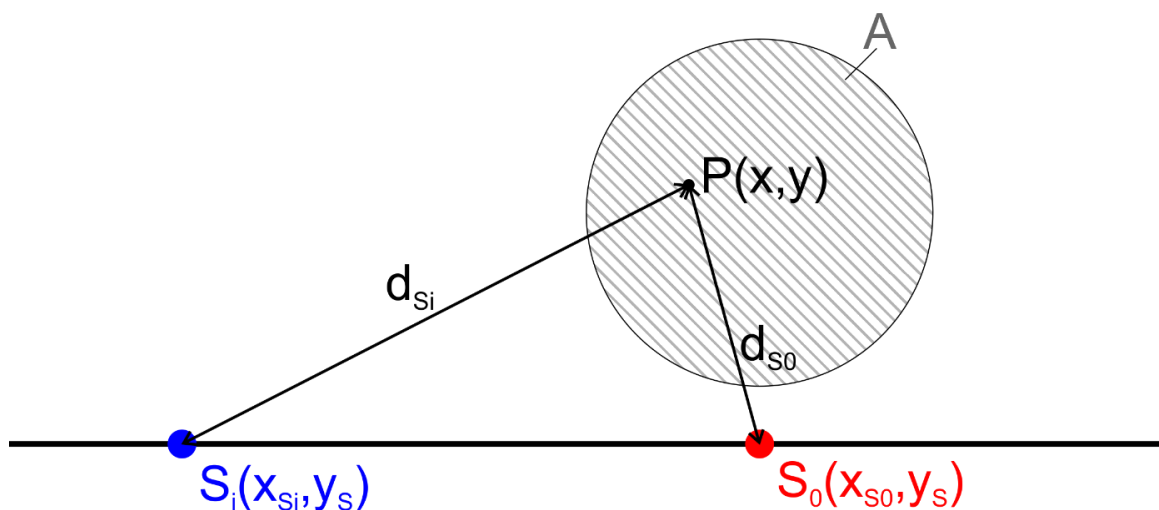
Figure 15: Fundamental concept of the model

The average travel time gain weighted by the settlement density $\delta_P(x, y)$ can thus be expressed as follows:

$$T = \frac{\iint_{P \in A} \delta_P \cdot \Delta t_P \cdot dA}{\iint_{P \in A} \delta_P \cdot dA} \tag{13}$$

Where both the numerator and the denominator are integrals over the settlement area A. Inserting equation (12) into equation (13) yields:

$$T = TT_{rail} \, S_i S_0 + \frac{\iint_{P \in A} \delta_P \cdot TT_{feeder} \, S_0 P \cdot dA}{\iint_{P \in A} \delta_P \cdot dA} - \frac{\iint_{P \in A} \delta_P \cdot TT_{feeder} \, S_i P \cdot dA}{\iint_{P \in A} \delta_P \cdot dA} \tag{14}$$

The different travel times contained in equation (14) are expressed as stated in the subsequent sections.

5.3.2 Rail

The rail travel time between the two possible stations is the distance divided by the <u>top speed</u> on the particular section under consideration, thus:

$$TT_{rail} \, S_i S_0 = \frac{x_{S0} - x_{Si}}{v_{rail}} \tag{15}$$

Acceleration and decelerations can be neglected. Figure 16 shows a generic speed profile between two train stops A & B. If the station B is moved closer to A (or further away), a slice is cut out (or added) in the middle section where the train runs at top speed, while the deceleration process is just translated to the left (or the right depending on the direction B is moved).
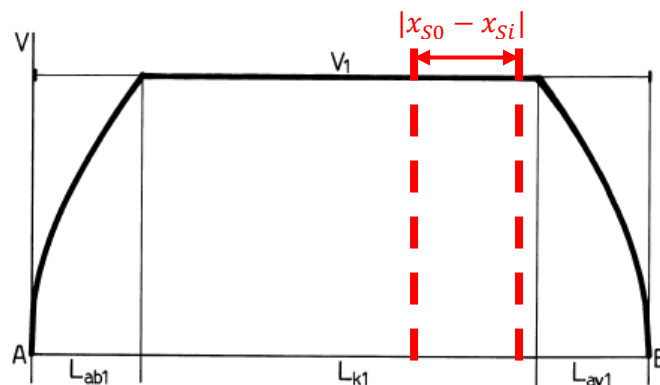
Figure 16: Speed profile between two train stops A & B
Source: Weidmann (2011)

5.3.3 Car feeder

The travel times $TT_{feeder}\,S_0P$ and $TT_{feeder}\,S_iP$ are both computed the same way. They depend on the choice of the feeder system. We will first explain their derivation for a car-based feeder system.

The car feeder system being a **spatially continuous and direct mode of transport**, the travel time is the distance divided by the <u>average speed</u>. In contrast to the train where only a delta-distance enters into the calculation, the entire feeder trip from departure to arrival is modelled. The distance is further augmented by a detour factor to account for the difference in length between the aerial distance and effective route taken on the road network. In this case, we assume a detour factor D_f of 1,5 as found out by (Meeder, 2015). The travel times in equation (14) thus become:

$$TT_{car}\,S_0P = \frac{d_{S0,P} \cdot D_f}{v_{car}}$$

$$TT_{car}\,S_iP = \frac{d_{Si,P} \cdot D_f}{v_{car}}$$

(16)

Inserting equations (15) and (16) into (14), we obtain:

$$T = \frac{x_{S0} - x_{Si}}{v_{rail}} + \frac{D_f}{v_{car}} \cdot \underbrace{\frac{\iint_{P \in A} \delta_P \cdot d_{S0,P} \cdot dA}{\iint_{P \in A} \delta_P \cdot dA}}_{D_{S0}} - \frac{D_f}{v_{car}} \cdot \underbrace{\frac{\iint_{P \in A} \delta_P \cdot d_{Si,P} \cdot dA}{\iint_{P \in A} \delta_P \cdot dA}}_{D_{Si}}$$

(17)

The fractions D_{S0} and D_{Si} describe the average distance between the points of the settlement area A and the station location S_0 respectively S_i. The computation of such an average distance can either happen numerically by approximation of the integral or in some well-defined special cases also through a – non-trivial – analytical mathematical formula. We will further elaborate on this point in chapter 7.

From equation (17), we can see that speeds of rail and car are the only parameters left for definition (next to those of the built environment described above under 5.1). Their influence will be investigated through the generic test case.

5.3.4 Bus feeder

The calculation of bus travel times to stations requires prior definition of a bus network. It uses the line density as an input parameter: here we define 'line density' as the number of lines in the main cross-section of the town. In the example shown in Figure 17, the line density is 3, although the total number of lines is 6. Both variables should thus not be confounded. The bus network is consolidated in a way that the maximum distance from any point in the settlement area to the bus line is minimal. The passage from conventional to autonomous buses allows an increase of the line-density.

The line-based bus network being a **spatially discrete feeder** system, the travel times in equation (14) take a more complex form than for the car-based feeder system. First of all, travel times need to be split up in a bus ride time and a walking time. Furthermore, the bus ride time does not correspond to the aerial distance between the bus stop and the station (augmented by the detour factor), but follows the form given by the bus network (augmented by the detour factor).
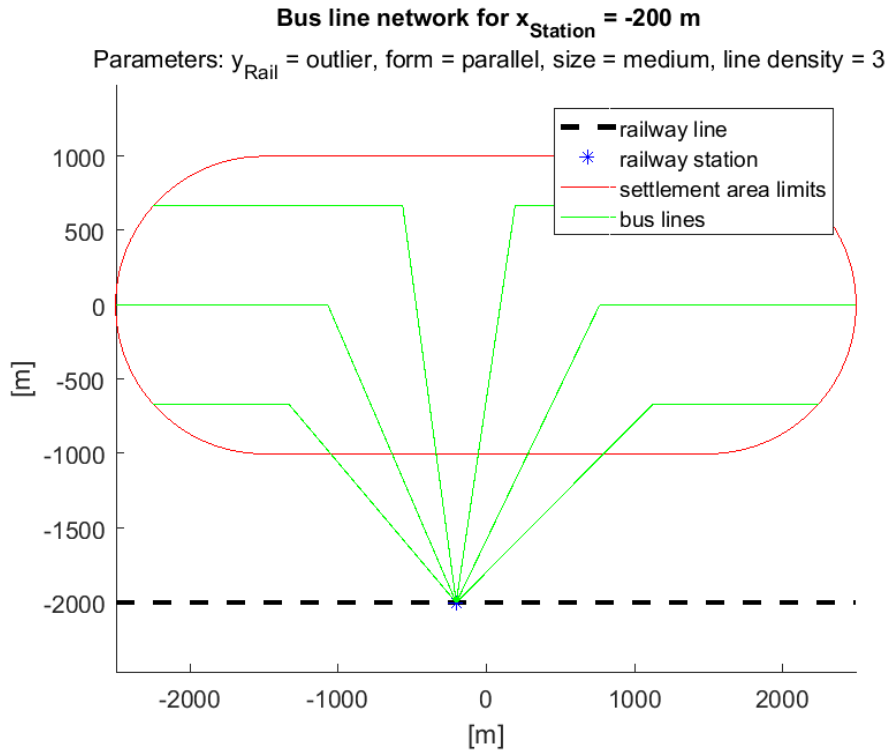
Figure 17: Example of bus network

The travel times thus become:

$$TT_{bus} \, S_i P = \frac{d_{bus} \cdot D_f}{v_{bus}} + \frac{d_{walk} \cdot D_{f,walk}}{v_{walk}} \tag{18}$$

For each point, d_{walk} is the aerial distance to the nearest bus line, which is afterwards augmented by a detour factor for walking of 1,4 (Meeder, 2015). v_{walk} is assumed to be 6 km/h. We assume furthermore, that people whose origin/destination is less than 300 m away from the station walk directly there without using a bus line.

For the bus feeder system, the following parameters are yet undefined and their influence will be investigated through the generic test cases:

- Speeds of bus and rail,
- Line density.

The bus model provides as a result not only the optimal station location form a travel time point of view, but also the riders per day on the different bus lines. The calculation is done according

to the procedure described by Weidmann (2013). The factors linking the actual number of inhabitants in a given area to the number of weighted inhabitants ("Ansprechbarkeitswerte") are given in Table 6.

Table 6: Ansprechbarkeitswerte

Walking distance	Factor
≤ 250 m	0.8
≤ 500 m	0.5
≤ 1000 m	0.25
> 1000 m	0

Furthermore, we assume **60 public transport riders per weighted inhabitant per year** (value for agglomerations) (Weidmann, 2013). Differences between working days (Monday – Friday) and weekends are neglected.

5.3.5 Multi-Station calculations

For long-stretched towns parallel to the railway line, the computations laid down before are repeated for a setting with two stations. In this section, we briefly explain the additional assumptions made for these calculations.

5.3.5.1 Car feeder

The calculation does not greatly differ from the one for a single station. For each point P in the settlement area, Δt_P is now defined as follows:

$$\Delta t_P = \min\{\Delta t_{P,Station\ 1}, \Delta t_{P,Station\ 2}\} \tag{19}$$

Where $\Delta t_{P,Station\ 1}$ and $\Delta t_{P,Station\ 2}$ are each calculated according to equation (12). Afterwards, computation of T happens normally according to equation (13).

The reference case stays the same as for the one-station calculation: a single station centrally located (x-axis-wise). For passengers alighting at the second station, we need to take into account that the train has extra stop compared to the reference case. The time loss for the latter is assumed to be **2 min** for dwell time, acceleration and deceleration, independently of the train speed. This is certainly a simplification, but we believe it is suitable for the degree of precision required by this type of calculation. Hence, $\Delta t_{P,Station\ 2}$ is now:

$$\Delta t_{P,Station\ 2} = TT_{rail}\ S_i S_0 + TT_{feeder}\ S_0 P - TT_{feeder}\ S_i P + 2min \tag{20}$$

5.3.5.2   Bus feeder

Δt_P stays defined the same way as for the car feeder system (equation (19)). The time loss for the additional train stops is also identical (2 min). The consolidation of the bus network differs, however, from the single-station-setting, as it needs to take into account the catchment areas of the two railway stations under consideration.

The delimiting line which separates those two catchment areas is the geometric locus where travel times via both stations are equal. If one makes the simplifying assumption that bus lines are direct (which they are not, but we view it as a suitable approximation for this specific question), the shape of the delimiting line is one branch of a hyperbole (the geometric locus where the difference of the distances to two given points, the focal points of the hyperbole, is constant). Figure 18 shows an example of a bus network for a two-station-setting. The pink dotted line is the hyperbole-branch which separates the two catchment areas. Its focal points are the two stations. When consolidating the bus network, we furthermore discard bus lines shorter than 500 m.
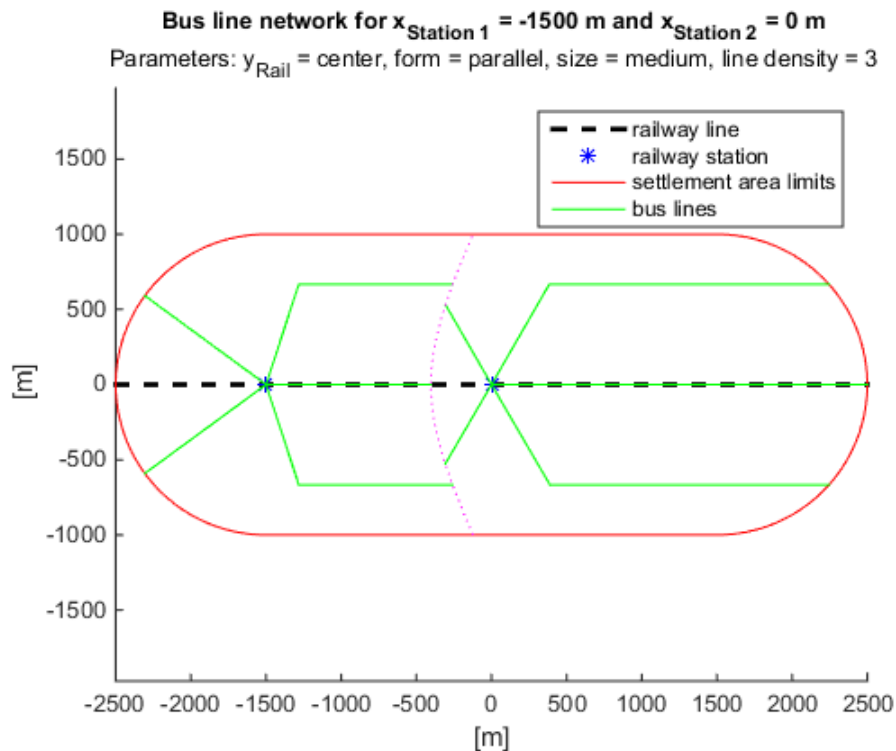
Figure 18: Example of bus network with 2 stations

All possible combinations of station locations are calculated. There are, however, the following two special situations:

1. If the delimiting line is fully located outside of the settlement area (to the left), only the 2nd station is considered and we are relegated to the single-station-case (as having multiple stations does not provide any benefit).

2. Similarly, if the two stations are too close (or even identical), such that alighting at the 2nd one does not yield better travel times than alighting at the 1st one, only the latter is

considered for onward calculations. We are again relegated to the single-station-case. Mathematically speaking, such a situation corresponds to the special stetting where the delimiting hyperbole degenerates into an empty set.

5.3.6 Simulation environments

The previously described calculations were implemented in MATLAB. 5 different codes (with common sub-features) were used:

1. **System comparison:** it compares the travel times to the station for the different feeder systems: car and both conventional and autonomous bus. For cars, automation does not change any parameters of the methodology. For buses, the lines density is increased. In total 11 different simulations were done. No optimization regarding the station location is done is this type of simulations.

2. **Optimal station location for car-based feeder system:** it calculates the travel time gains realizable for the main origin-destination pair as a function of the station location for car-based feeder systems. Further outputs are the rotation times of the vehicles (maximum and average) as well as the spread of the travel time gains over the settlement area.

   Two different variations of the code are used for single, respectively multi-station settings:

   a.   35 single-station scenarios

   b.   10 multi-station scenarios

3. **Optimal station location for bus-based feeder system:** it calculates the travel time gains realizable for the main origin-destination pair as a function of the station location for bus-based feeder systems. Further outputs are the rotation times of the vehicles (maximum and average), the number of riders (total and per line), the total length of the lines as well as the spread of the travel times gains over the settlement area and the walking distances.

   Two different variations of the code are used for single, respectively multi-station settings:

   a.   46 single-station scenarios

   b.   11 multi-station scenarios

5.4   Scenario definition

The scenarios of the generic test cases can be divided into three major clusters:

- Influence of built environment (Table 7)

- Influence of speed (Table 8)

    o   The chosen speed values are rather extreme cases. This is a deliberate choice in order to make sure that the influence can be seen and is not lost in the inaccuracy of the model.

- Influence of line densities (Table 9)

    o   We again chose to assume a rather extreme increase (i.e. a doubling of the line densities) in order to see how the output behaves and to avoid that the effects are overridden by the inaccuracy of the model.

In the subsequent tables, each scenario is listed with its respective input parameters and the simulation environments applied to it.

Table 7: Scenario list: Influence of built environment

Case Nbr	Form	Size	Location of rail-way line	Settlement density distribution	Speed of rail	Speed of SAV	Speed of bus	Bus line density	Car single station	Car multi station	Bus single station	Bus multi station	System comparison
0.0	Circular	medium	centre	homogeneous	80	30	20	3	X		X		X
0.1	Circular	small	centre	homogeneous				2	X		X		X
0.2	Circular	medium	centre	inhomogeneous				3	X		X		
0.3	Circular	large	centre	inhomogeneous				6	X		X		X
1.0	Parallel	medium	centre	homogeneous	80	30	20	3	X	X	X	X	X
1.1	Parallel	small	centre	homogeneous				2	X	X	X	X	
1.2	Parallel	large	centre	inhomogeneous				6	X	X	X	X	
2.0	Perpendicular	medium	centre	homogeneous	80	30	20	3	X		X		X
2.1	Perpendicular	small	centre	homogeneous				2	X		X		
2.2	Perpendicular	large	centre	inhomogeneous				6	X		X		
3.0	Circular	medium	tangent	homogeneous	80	30	20	3	X		X		X
3.1	Circular	small	tangent	homogeneous				2	X		X		
3.2	Circular	large	tangent	inhomogeneous				6	X		X		
4.0	Circular	medium	outlier	homogeneous	80	30	20	3	X		X		X
4.1	Circular	small	outlier	homogeneous				2	X		X		
4.2	Circular	large	outlier	inhomogeneous				6	X		X		
5.0	Parallel	medium	tangent	homogeneous	80	30	20	3	X	X	X	X	X
5.1	Parallel	large	tangent	inhomogeneous				6	X	X	X		
6.0	Parallel	medium	outlier	homogeneous	80	30	20	3	X	X	X	X	X
6.1	Parallel	small	outlier	homogeneous				2	X	X	X		
7.0	Perpendicular	medium	tangent	homogeneous	80	30	20	3	X		X		X
7.1	Perpendicular	large	tangent	inhomogeneous				6	X		X		
8.0	Perpendicular	medium	outlier	homogeneous	80	30	20	3	X		X		X
8.1	Perpendicular	small	outlier	homogeneous				2	X		X		

Table 8: Scenario list: Influence of speeds

Case Nbr	Form	Size	Location of railway line	Settlement density distribution	Speed of rail	Speed of SAV	Speed of bus	Bus line density	Car single station	Car multi station	Bus single station	Bus multi station	System comparison
9.0	Circular	medium	centre	homogeneous	50	50	30	3	X		X		
9.1	Circular	small	centre	homogeneous				2	X		X		
9.2	Circular	large	centre	inhomogeneous				6	X		X		
10.1	Parallel	medium	centre	homogeneous	50	50	30	3	X	X	X	X	
10.2	Perpendicular	medium	centre	homogeneous	50	50	30	3	X		X		
11.1	Circular	medium	tangent	homogeneous	50	50	30	3	X		X		
11.2	Circular	medium	outlier	homogeneous	50	50	30	3	X		X		
12.1	Parallel	medium	tangent	homogeneous	50	50	30	3	X	X	X	X	
12.2	Parallel	medium	outlier	homogeneous	50	50	30	3	X	X	X	X	
12.3	Perpendicular	medium	tangent	homogeneous	50	50	30	3	X		X		
12.4	Perpendicular	medium	outlier	homogeneous	50	50	30	3	X		X		

Table 9: Scenario list: Influence of line densities

Case Nbr	Form	Size	Location of railway line	Settlement density distribution	Speed of rail	Speed of SAV	Speed of bus	Bus line density	Car single station	Car multi station	Bus single station	Bus multi station	System comparison
13.0	Circular	medium	centre	homogeneous	80	30	20	6			X		X
13.1	Circular	small	centre	homogeneous				4			X		X
13.2	Circular	large	centre	inhomogeneous				12			X		X
14.1	Parallel	medium	centre	homogeneous	80	30	20	6			X	X	X
14.2	Perpendicular	medium	centre	homogeneous	80	30	30	6			X		X
15.1	Circular	medium	tangent	homogeneous	80	30	20	6			X		X
15.2	Circular	medium	outlier	homogeneous	80	30	20	6			X		X
16.1	Parallel	medium	tangent	homogeneous	80	30	20	6			X	X	X
16.2	Parallel	medium	outlier	homogeneous	80	30	20	6			X	X	X
16.3	Perpendicular	medium	tangent	homogeneous	80	30	20	6			X		X
16.4	Perpendicular	medium	outlier	homogeneous	80	30	20	6			X		X

6 Results of Generic Test Cases (Q2-Q4)

6.1 Question 2

This section summarizes the results of the generic test cases with respect to Question 2 which reads follows:

What are the achievable benefits by using autonomous shared cars and autonomous buses as feeder services compared to the status quo?

The subsequent explanations are based on the application of simulation environment 1: System comparison. The results are shown on one test case chosen as a characteristic example. The results of all the other test cases are very similar in nature and magnitude.

The purpose of this section is to compare the performance of the different types of feeder systems in terms of travel time and ridership potential. The search for the optimal location of the railway station is not yet of interest here.

6.1.1 Average Travel Times to Station

Figure 19 shows the average travel times to the station for the generic test cases 3.0 / 15.1 (cf. Table 7 and Table 9).

Average Travel Times to Station as function of x$_{Station}$

Parameters: y$_{Rail}$ = tangent, form = circle, size = medium

conventional line density = 3, autonomous line density = 6

density distribution = homogeneous, V$_{bus}$ = 20 km/h, V$_{SAC}$ = 30 km/h

- Conventional bus travel times to station
- Autonomous bus travel times to station
- Car travel times to station

Zero always corresponds to middle of the town

Figure 19: Average travel times to station as function of its location (cases 3.0 / 15.1)

First of all, one can see that the travel times for the autonomous bus network with a doubled line density are not much shorter than those of the conventional bus network. In absolute numbers, the difference is roughly one minute. The reason is that only the access/egress times by walk to/from the bus stop are shortened, but the travelled distance on the bus does not change in a significant way.

Furthermore, the line density of the conventional network is already quite high so that the average walking distance is fairly low: the town size medium with a diameter D of 2000 m and the line density of 3 yield an average spacing between the bus lines of 667 m. The catchment radius (equivalent to the maximum walking distance) is 333 m which yields an average walking distance (assuming homogeneous settlement density) of 167 m for the conventional bus network (see also red curve in Figure 20). The doubling of the line density cuts the average walking distance by another 50% (see green curve in Figure 20). The reduction of the average walking distance by 83 m is what corresponds to the one minute of travel time difference.

The difference in travel time between bus feeder and car feeder is primarily due to the difference of their average speeds. The latter is again due to the fact that the bus feeder has intermediate stops to let passengers board or alight, while the car feeder does not. For centrally located stations (position of the railway station near x=0), the difference in absolute values is a bit less than 5 min. Only looking at the short travel distance between station and final origin/destination, this is a significant difference. However, if one considers the total door-to-door travel time, the relative share of the 5 min difference decreases a lot. One shall thus not overestimate this difference. The 5 minutes also correspond to the time laps during which passengers are assumed to arrive at the station with the autonomous car-based feeder before the train departure (see section 4.2).

One should bear in mind that the adoption of a car-based feeder system at heavily used stations necessarily requires the arrivals of the vehicles to be spread out over a certain period of time before the scheduled train departure in order to allow their handling by the road network and the drop-off facility (see chapter 4). If one adds this time laps to the car feeder travel times, the difference between car and bus closes further. For a bus-based feeder, such a temporal spread before the train departure is not needed, as the number of vehicles is much smaller. **In other words, as soon as the capacity of the drop-off area is widely utilized such that arrivals effectively need to spread out over the 5 minutes, the bus-based feeder is also competitive in terms of travel time.**

6.1.2 Ridership and the influence of line density

The willingness of people to use public transport is, among others, dependent on the walking distance to the nearest access point of the system. The methodology to estimate the ridership based on the walking distances has been explained in section 5.3.4. This section investigates the effect of an increased line density on walking distances and ridership.

Figure 20 shows the average walking distance as function of the station location, for both the conventional and the autonomous bus network. One can see that the walking distances are cut by almost 50%. Figure 21 shows the corresponding number of bus riders per day per direction (based on the assumptions presented in sections 5.3.4). The ridership can be

increased by only around 20%. The reason for the under-proportional increase lies in the "Ansprechbarkeitswerte" given in Table 6.

Average Walking Distance as function of x_Station

Parameters: y_{Rail} = tangent, form = circle, size = medium

conventional line density = 3, autonomous line density = 6
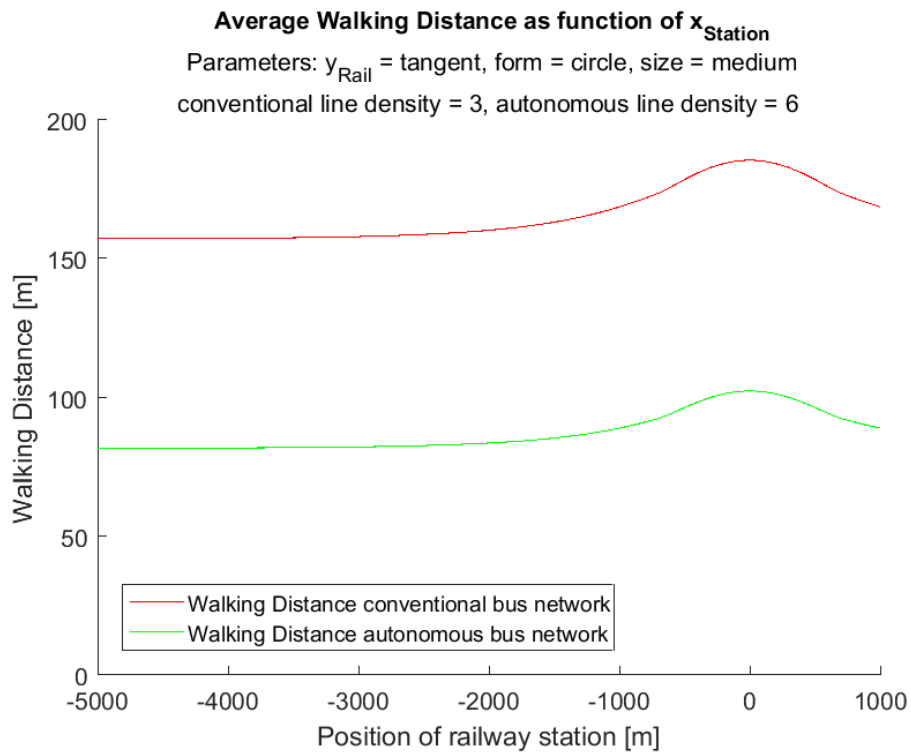
Figure 20: Walking distance as function station location (cases 3.0 / 15.1)

Total riders per day per direction as function of x_Station

Parameters: y_{Rail} = tangent, form = circle, size = medium

conventional line density = 3, autonomous line density = 6
density distribution = homogeneous
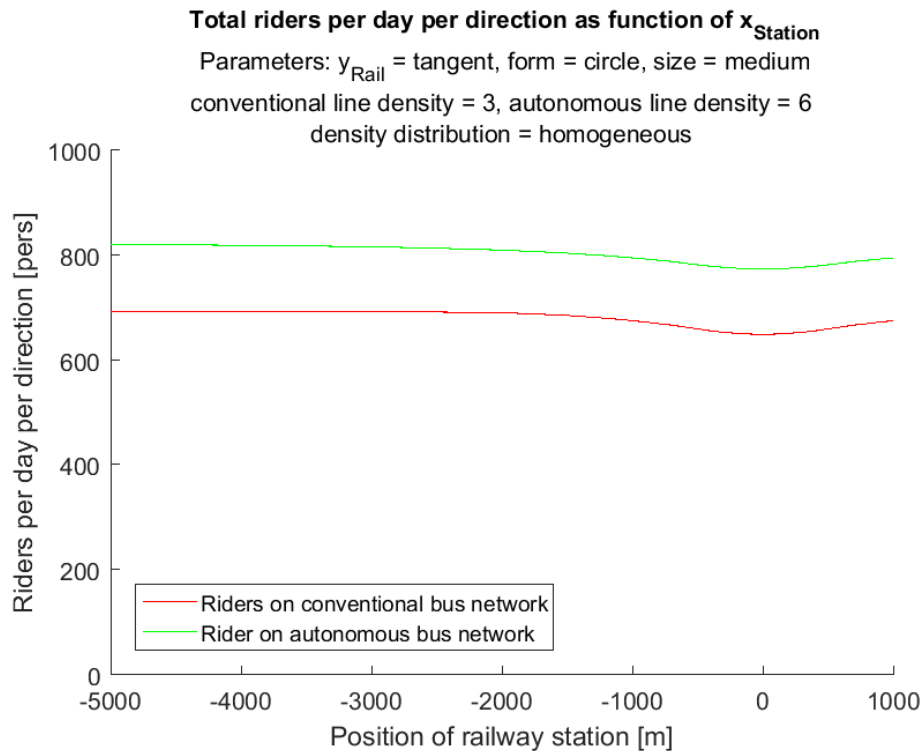
Figure 21: Riders per day per direction as function of station location (cases 3.0 / 15.1)
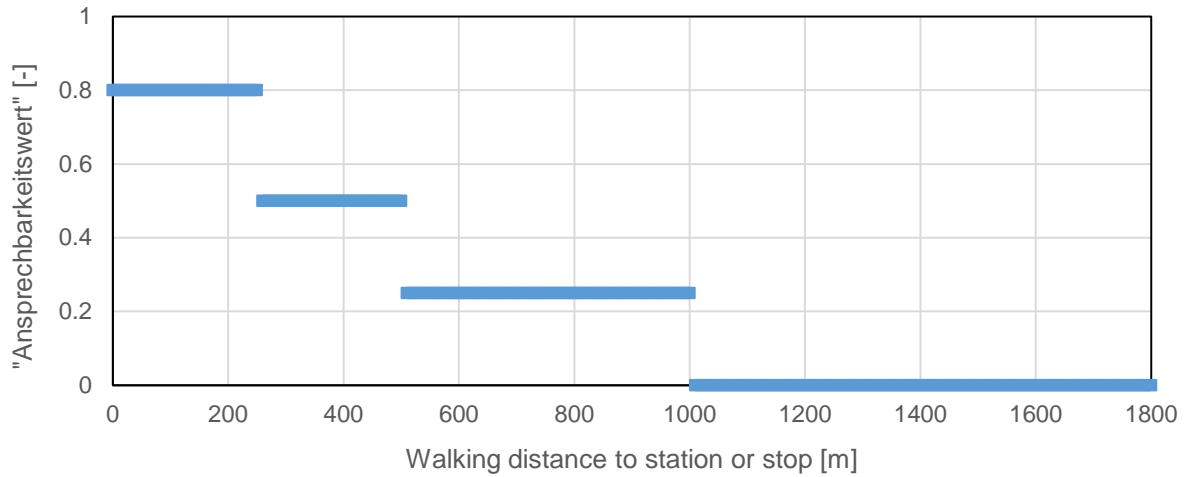
Figure 22: Function f showing "Ansprechbarkeitswerte" as function of walking distance w

Plotting the "Ansprechbarkeitswerte" over the walking distance w, we obtain the piecewise constant function f shown in Figure 22. Let r now be the catchment radius around a bus line. The average "Ansprechbarkeitswert" G over this catchment can thus be calculated as follows:

$$G(r) = \frac{1}{r} \cdot \int_0^r f(w) \, dw \tag{21}$$

Given the discontinuity of f, we obtain a piecewise defined function G shown by the solid graphs in Figure 23. It is formed by a sequence of three hyperbolic curves. It is continuous, but not continuously differentiable.
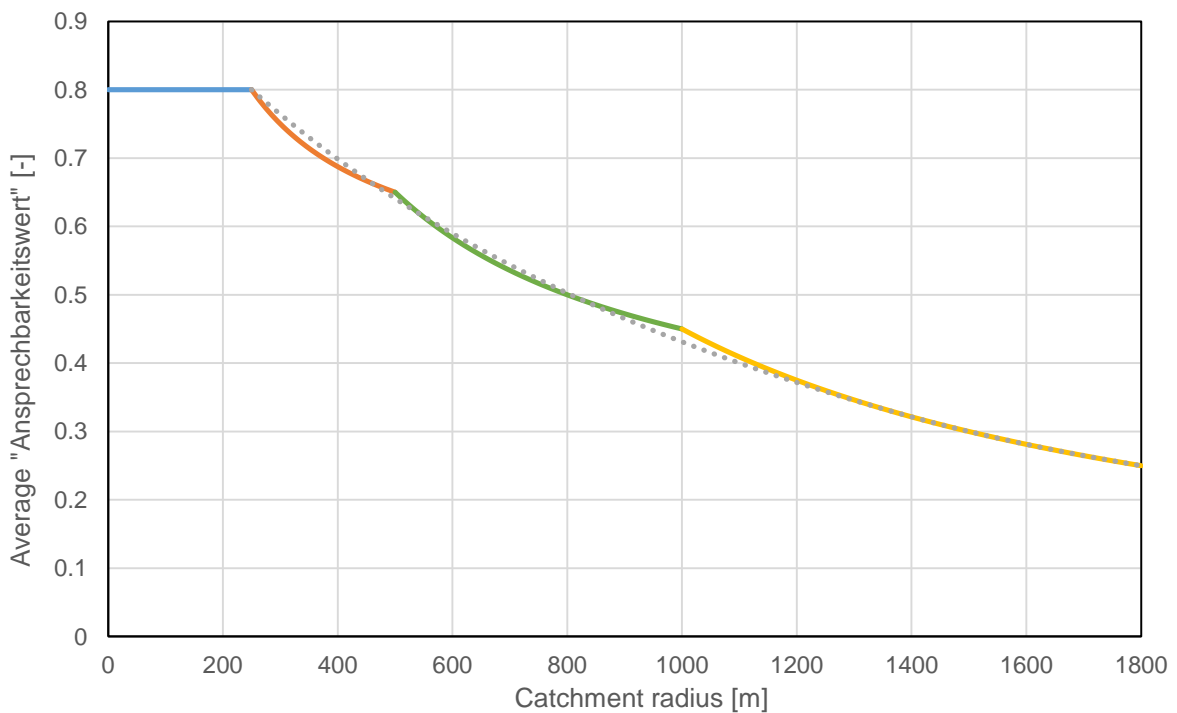
Figure 23: Average „Ansprechbarkeitswert" as function of catchment radius r

Analytically, it is given by the following expression:

$$G(r) = \begin{cases} 0.8 & \text{if } r \leq 250 \\ 0.5 + \dfrac{75}{r} & \text{if } 250 \leq r \leq 500 \\ 0.25 + \dfrac{200}{r} & \text{if } 500 \leq r \leq 1000 \\ \dfrac{450}{r} & \text{if } r \geq 1000 \end{cases} \tag{22}$$

If we let D be the diameter of the considered town and n_0 the number of already existing bus lines, then the catchment radius is given by:

$$r(n) = \frac{D}{2 \cdot n} \cdot D_f \tag{23}$$

Where D_f is the detour factor equal to 1,4 according to Meeder (2015). The relative ridership gain through the addition of one supplementary bus line can be calculated as follows:

$$\delta G = \frac{G[r(n+1)] - G[r(n)]}{G[r(n)]} \tag{24}$$

Since $r(n)$ depends on D, δG does so as well. Figure 24 shows the graphical representation for different town diameters D. For the generation of these graphs, the function $G(r)$ has been flattened around the points where the three hyperbolic sections meet in order to obtain a continuously differentiable function (dotted line in Figure 23).

Let us now compare these theoretical results to those obtained through the simulation (given in Appendix A1.3). For medium-size towns ($D = 2000m$ ➔ orange curve), we obtain experimental increases in ridership between 15% and 20% by passing from 3 lines to 6 lines. Summing up the relative ridership increases for $n = \{3,4,5\}$ according to Figure 24, we obtain an increase of 20%, which matches well with the experimental data. For small towns ($D = 1000m$ ➔ fair blue curve), the passage from 2 to 4 lines (sum for $n = \{2,3\}$) yields 10% according to Figure 24. This matches well with the 9% of experimentally determined increase. Finally, for the large town ($D = 4000m$ ➔ yellow curve), the sum of relative ridership increases for $n = \{6,...,11\}$ yields 20% which again matches with the experimental data.

The graphs given in Figure 24 can thus help in practice to get a first rough and quick estimation of how much additional bus lines can bring in terms of ridership.
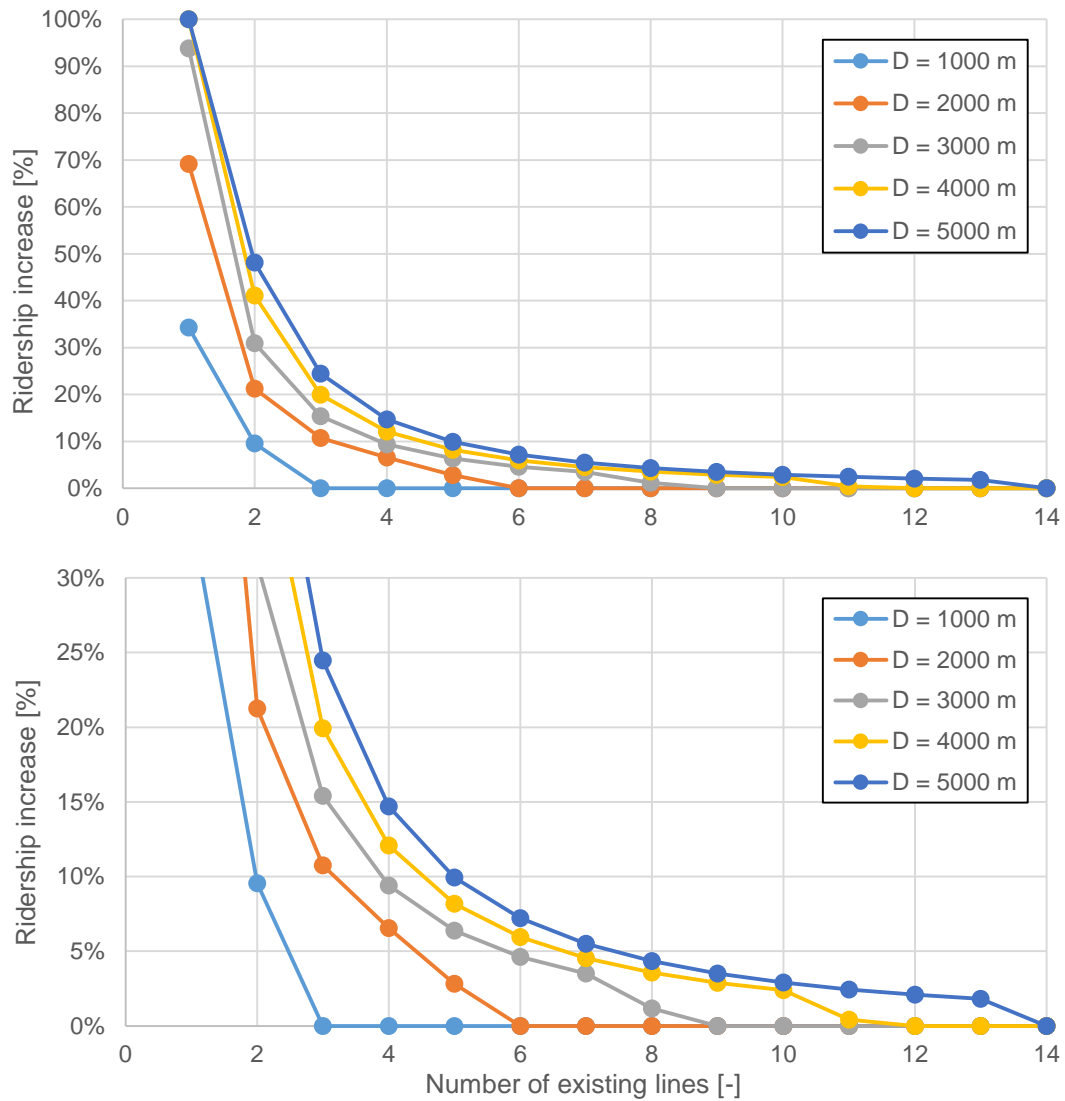
Figure 24: Ridership increase through addition of one bus line
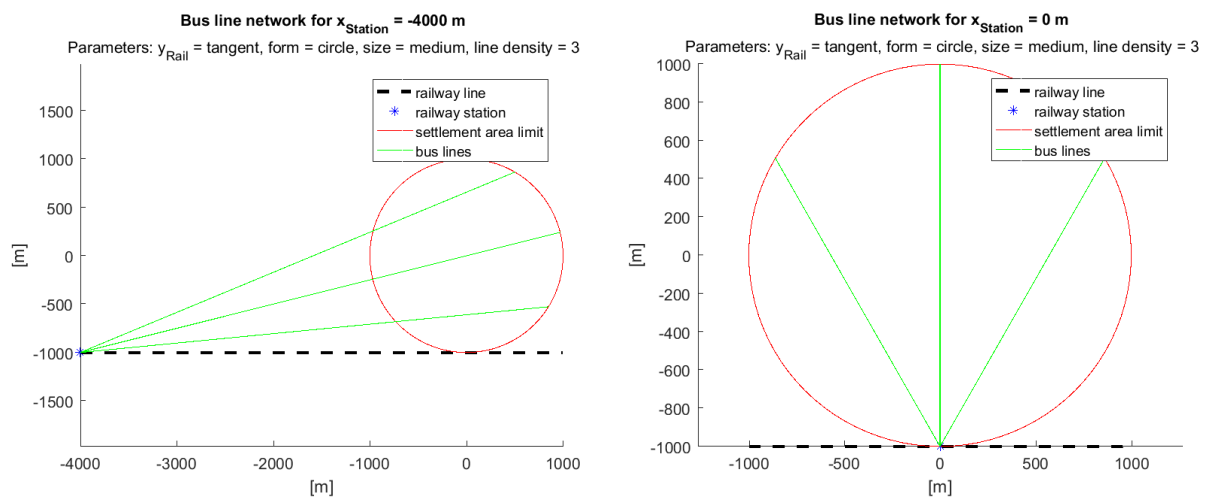
Figure 25: Examples of bus networks for circular towns (case 3.0)

When looking at Figure 20, it seems on the first glance counter-intuitive that the walking distance increases and consecutively the ridership decreases with more centrally located stations. The reason for these results lies in the generation of the bus network. Figure 25 shows the conventional bus network (line density 3) for x = - 4000 m and x = 0m. One recognizes that on the left picture the three bus lines manage to provide a better and more homogeneous coverage of the settlement area than on the right picture. This is a specialty of circular towns and does not apply to parallel or perpendicular ones.

6.1.3 Conclusions

An increase of the line density on the bus network, e.g. thanks to automation, does not lead to significant travel time savings. The travel distance on the vehicle cannot be shortened much. Only the access/egress times are shortened. The latter, however, allow for a significant, although under-proportional, increase in ridership.

Travel times via a car-based feeder system are significantly lower than those of a bus-based feeder, because of:

- The shorter ride distance (does not apply in case of circular towns),

- The higher speed,

- The non-existent access/egress times.

In absolute numbers, the difference in roughly 5 minutes of travel time for station locations close to the town centre.

6.2 Question 3

This section summarizes the results of the generic test cases with respect to Question 3 which reads follows:

> **What are the benefits in terms of travel time, if railway stations are relocated? Which implications would such a relocation have on urban planning? Is a relocation advisable from the urban planning perspective?**

The subsequent explanations are based on the application of simulation environments 2a and 3a.

6.2.1 General principles

Figure 26 shows an example (case 3.0) of the graph representing the travel time savings that can be realized through a relocation of the station as a function of its location. The reference case is a station which is centrally located (in x-axis-direction), thus the curve always passes through the origin of the coordinate system. Figure 27 shows the same graph for case 11.1 with different speeds of rail and car-based feeder. We notice that the maximum achievable

travel time savings increase, while the optimal location where those can be realized is significantly shifted to the left. Appendix A1 provides a full overview of all results of the more than 100 simulations that were run as part of this research. On the following pages, we will briefly present the main conclusions.
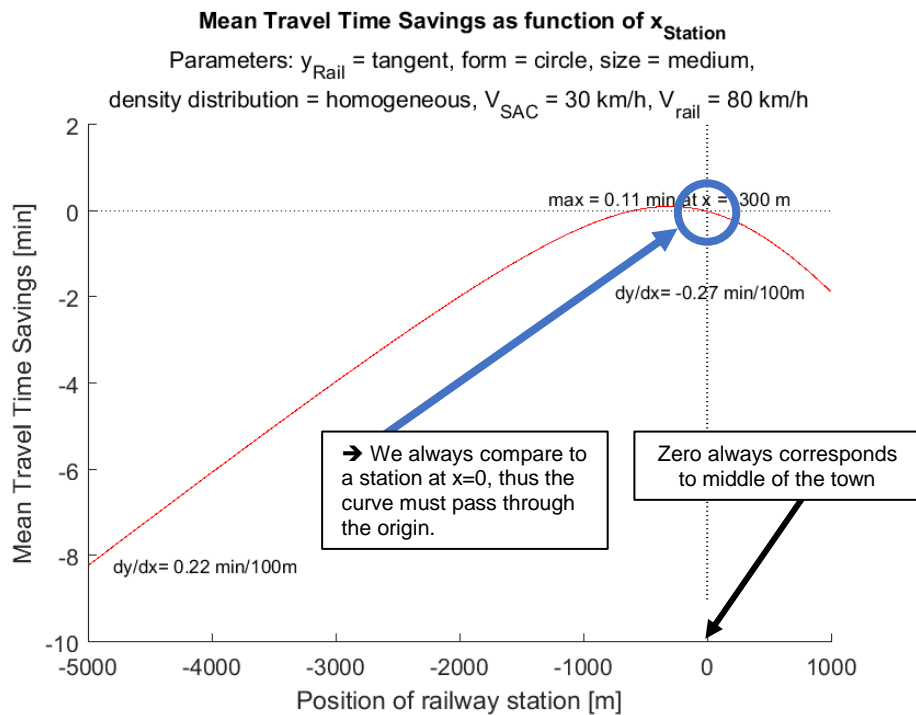
Figure 26: Mean Travel Time Savings as function station location (case 3.0)
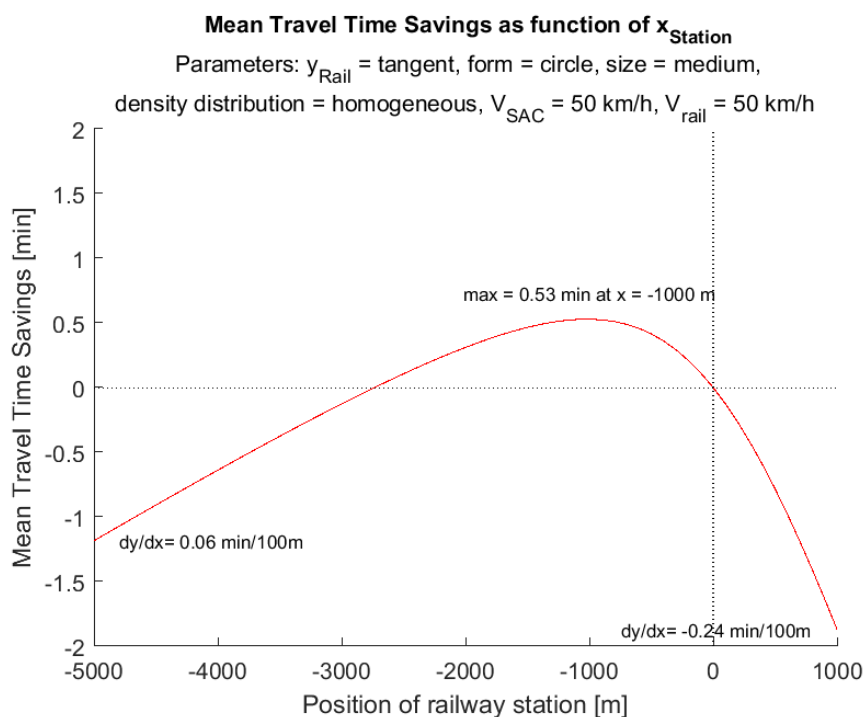
Figure 27: Mean Travel Time Savings as function station location (case 11.1)

6.2.2 Comparing Car and Bus

The full comparison of the numerical results of the simulations 2a for car-based feeders and 3a for bus-based feeders can be found in Appendix A1.1. The conclusions one can draw from these results are as follows:

1. **Optimal station location of car-based feeders is always left of the one for bus-based feeders.** An exception is the circular town with railway line passing centrally through it: in this specific setting the optimal location of bus-feeders is further left the one of car-feeders, as a fully central station does not allow good coverage of the town with the bus network – under the assumption of constant line density. The phenomenon is illustrated by Figure 28.
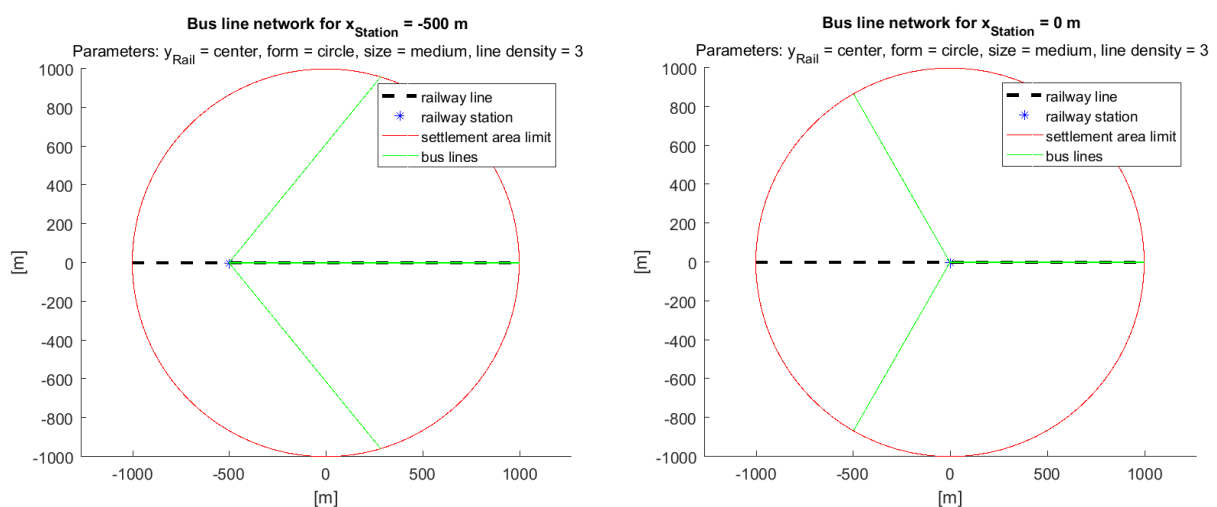
Figure 28: Bus network generation for setting circular-central

2. **The travel time gains that can be realized through a relocation of the station are generally higher for the car-feeder than for the bus-feeder.** An exception is here again the setting of the circular town with the railway line passing centrally through.

3. **The maximum achievable travel time gains stay relatively modest**, in general below 1 minute. Only through a positive combination of all influencing factors (high car speeds, low rail speeds, perpendicular town, railway line outside town), travel time gains of 1,5 minutes can be achieved. The travel time gain is thus so small that a relocation of station cannot be justified through it alone.

4. **The more similar the speeds of the feeders and the rail, the higher the differences between car-based feeder and bus-based feeder.** This means that for comparably high speeds on the railway line, the optimal location of the railway station is fairly robust with respect to a potential change of feeder service, while on secondary railway lines with low speeds, the robustness is not given to the same extent.

5. **The more centrally located the railway line compared to the town, the lower the differences between car-based feeder and bus-based feeder.** In return, this means that for railway lines located far outside the town centre, the optimal station locations tend to differ more between car-feeder and bus-feeder.

6.2.3 Influence of the position of the railway line

Appendix A1.2 provides the full results regarding the influence of the position of the railway line on the optimal station location. Based on these, one can draw the following conclusions:

1. **The further outside the railway line, the further left the optimal location of the railway station.** This statement is both valid for car-based feeders as well as bus-based feeders.

2. Also, **the further outside the railway line, the greater the differences between car and bus** (see point 6 under 6.2.2). The optimal station location for a car-based feeder system reacts more sensitively to the position of the railway line (and other changes in the built environment) than the optimal station location for a bus-based feeder system.

3. **Perpendicular towns, have the optimal locations of the railway station further left than circular towns.** A comparison with parallel towns in hardly meaningful in this case. In general, the further away parts of the town are located from the railway line, the further left the optimal location is.

4. **At low speed differences between the rail and the feeder, the position of the railway line compared to the town centre matters more than at higher speed differences.** This rallies with finding 5 of 6.2.2. Secondary railway lines with low speeds are thus more sensitive in this matter.

6.2.4 Influence of line density

Appendix A1.3 provides the full results regarding the influence of the bus line density on the optimal station location. Based on these, one can draw the following conclusions:

1. **The increase of the line density of bus networks does not have a notable effect on the optimal position of railway station.** Some smaller changes that could be observed can be attributed to rounding, as the simulation environment only deals with steps of 100 m. In this regard, the optimal location is very robust towards a passage from a conventional to an autonomous bus network.

2. **Similarly, the additional travel time savings attributable to a pure change of station location are almost identical for both autonomous and conventional bus networks.** This does not mean that no travel time gains at all are realizable. As section 6.1.1 has shown, there are travel time gains thanks to increased line density. For the simulations analysed here, these travel time gains are already contained in the reference location x=0. Simulation environment 3a only provides the travel time gains purely due to the relocation of the station and not the ones linked to a change of feeder system, or the introduction of a feeder system as a whole.

3. **The number of riders can be increased by about 15% to 20%.** However, this change is seen independently of the station location when passing from conventional to autonomous buses (see sections 6.1.1 and 6.1.2).

6.2.5 Influence of relative speed

Appendix A1.4 provides the full results regarding the influence of relative speed on the optimal station location. Based on these, one can draw the following conclusions:

1. **Speed has a very large influence on the optimal location of a station, both for car-based feeders as well as bus-based feeders.** For the two speed settings we have investigated (cases 0 to 8.0 versus cases 9.0 to 12.4), the differences that resulted for the optimal station location were in many cases higher than 500 m, some being beyond 1000 m or more.

2. **The influence of relative speed is much higher for car-based feeders than for bus-based feeders.** While for the former the differences between the two speed settings are in many cases more 1000 m, the same holds only rarely true for the latter.

3. **The influence of relative speed increases the further outside the railway line is located with respect to the town centre.** This is expectable, as the average distance to the station increases and thus the effect of speed weights more.

4. **The influence is also higher for parallel and perpendicular towns than for purely circular ones.** Figure 29 shows the mean travel time savings for the medium size circular town (railway line passing centrally through) for the two speed scenarios: the difference regarding the optimal location is - 400 m. Figure 30 displays the same comparison for the parallel town: the difference regarding the optimal location grows to - 1000 m. Finally, Figure 31 shows the same comparison for the perpendicular town: the difference of the optimal location is – 700 m. This result is again expectable, as parallel or perpendicular towns (of the same size parameter (small, medium, large)) are bigger than the circular ones, so that the average distances are higher too. Hence, speed plays a more important role.
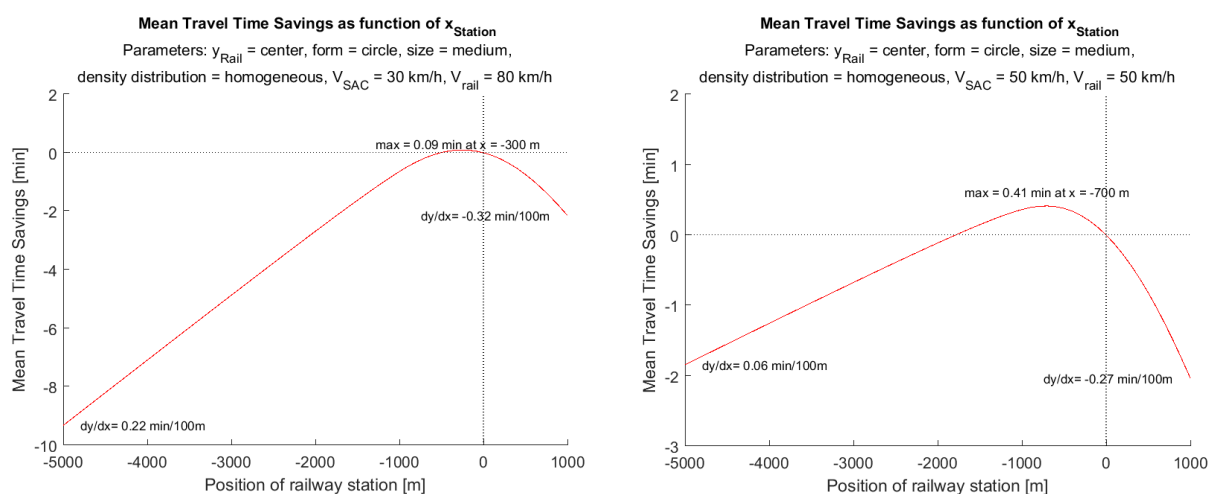
Figure 29: Influence of relative speed for circular town (comparing cases 0 and 9.0)
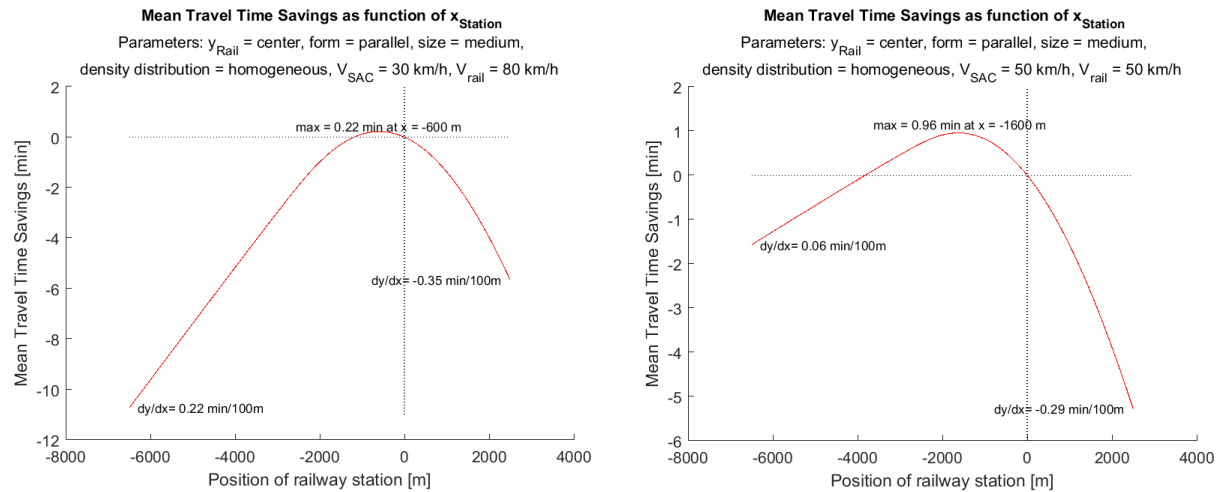
Figure 30: Influence of relative speed for parallel town (comparing cases 1.0 and 10.1)
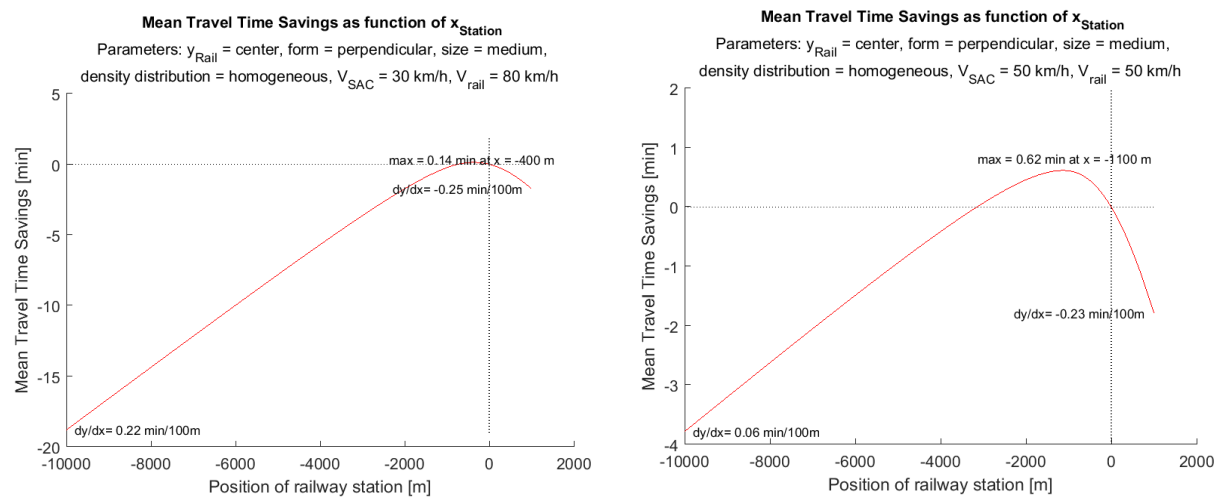
Figure 31: Influence of relative speed for perpendicular town (comparing cases 2.0 and 10.2)

6.2.6 Influence of settlement density

Regarding the influence of the settlement density, one can note the following by comparing cases 0 and 0.2: **an inhomogeneous density attracts the optimal station towards the areas of higher density.** This is an expectable finding and is confirmed for the simulation cases with large inhomogeneous towns: the optimal station location is not fully scaled together with the town size: the scaling effect is counterbalanced by the effect of inhomogeneity which attracts the optimal location again towards the centre (the area which has the higher density in the respective test cases).

6.2.7 Influence of town size

From Appendix A1.1, we can see that both the optimal location of the station and the resulting travel time savings are scaled together with the town size. These relationships can be

mathematically proven (see chapter 7). This means that in larger towns a potential relocation of the station can provide higher benefits in absolute travel times than in smaller towns.

6.2.8 General Conclusion

Summarizing the findings explained above, one notes that railway lines with comparably low speeds, passing outside the towns they serve are the least robust when it comes to changes of feeder systems. In regard to the form of the town, the perpendicular towns stretching far away from the railway line are the least robust. As both the optimal location and the realizable travel time savings are scaled with the size of the towns, large towns feature the highest travel time savings and are thus the most valuable for potential relocations.

6.3 Question 4

This section summarizes the results of the generic test cases with respect to Question 4 which reads follows:

What are the benefits in terms of travel time, if the station density along a railway line decreases (i.e. one or more stops can be omitted)? Which implications does it have on urban planning?

The opportunity of leaving out a station can be assessed in two different ways:

1. In parallel towns, we investigate how a second station influences the target variables (optimal station location, travel time savings, ridership). If they do not change much, the benefit of several stations in parallel towns is small. This approach uses simulation environments 2b and 3b. **This method addresses the case where one of two stations in the same town would be cancelled**.

2. Using the results we get from the application simulation environments 2a and 3a to the generic test cases, we can check, how far a station can be moved to the left while keeping the travel time savings above the threshold of -2 min (i.e. a travel time loss of two minutes). The two minutes are the supplement required for one additional train stop (see section 5.3.5). **This method addresses the case, where the station of a given town is cancelled and passengers need to travel by the feeder-service (of whichever kind) to the next town to take the train.**

6.3.1 Multiple stations in parallel towns

The full results of all test cases are provided in Appendix A1.5. Figure 32 shows an example of a contour plot indicating the travel time savings as a two-dimensional function of the two station locations. It only shows the upper-left half of the space. The lower-right half could be obtained through symmetry along the first diagonal. The first diagonal of Figure 32 (oblique blue-framed box) corresponds to the setting, where both stations are identical. Thus, if one plots the travel time savings on the first diagonal along as a function of the station location one obtains the function in Figure 33.
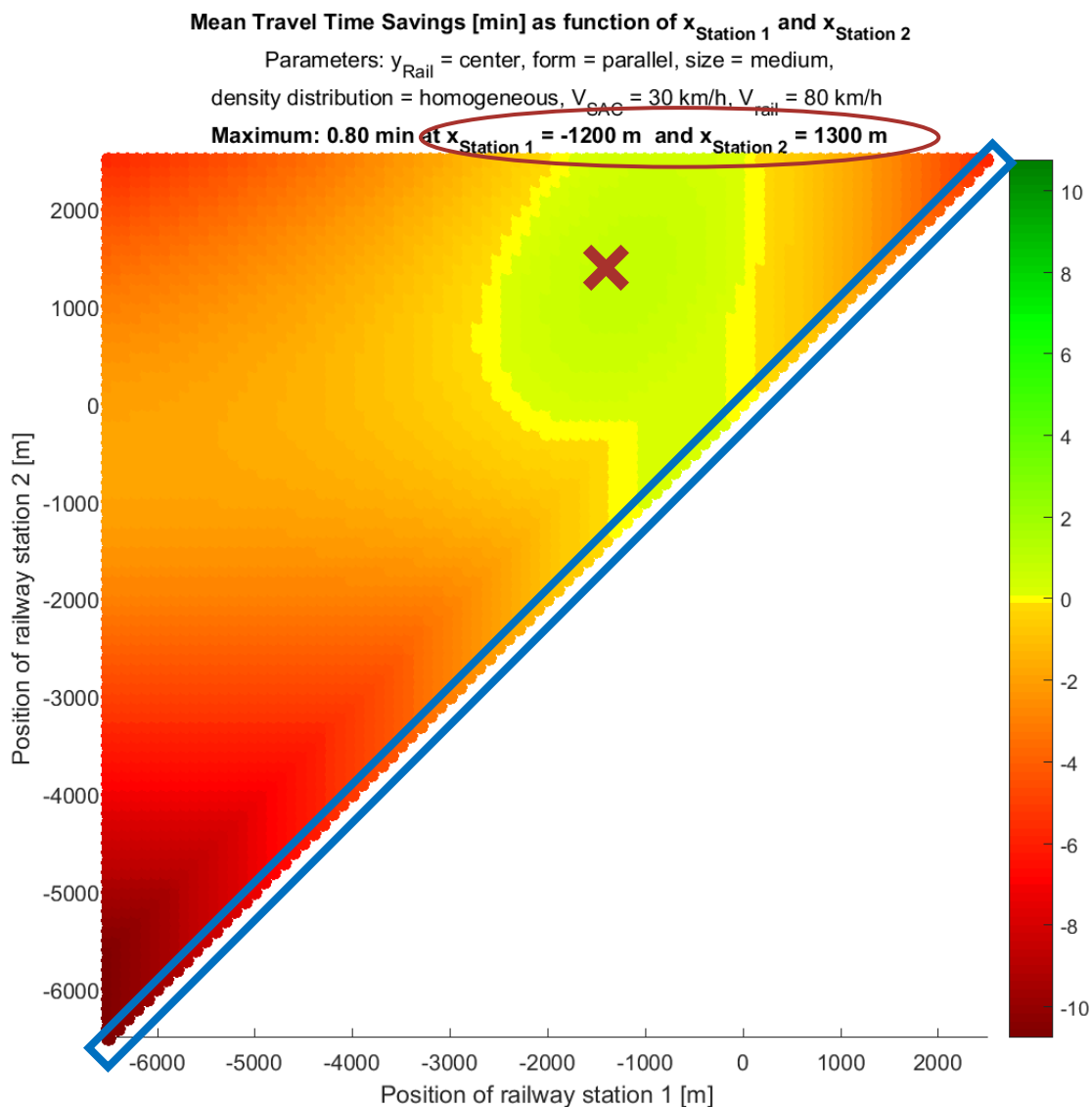
Figure 32: Travel Time Savings as two-dimensional function of stations locations (case 1.0)

On the basis of the results in Appendix A1.5, one can conclude the following:

1. **Additional travel time savings through the second station are relatively modest.** The difference for car-based feeders is most of the time below one minute. For bus-based feeders, the difference is generally higher, most of the time between one and two minutes, in one case above 2 minutes. The latter is case 1.2 of the large town. This can be explained by fact that the achievable travel time savings scale together with the size of the town.

2. **The additional travel time savings are larger for the bus than for the car.** A second station thus makes more sense for a bus-based feeder system than for a car-based feeder. One needs to bear in mind this fact when making decision concerning the establishment of potential new railway stations. **If one expects autonomous cars to take over the role as feeders, the new station might not reach (time-wise) the economic pay-back of the investment linked to its construction.**

Mean Travel Time Savings as function of x$_{Station}$

Parameters: y$_{Rail}$ = center, form = parallel, size = medium,

density distribution = homogeneous, V$_{SAC}$ = 30 km/h, V$_{rail}$ = 80 km/h
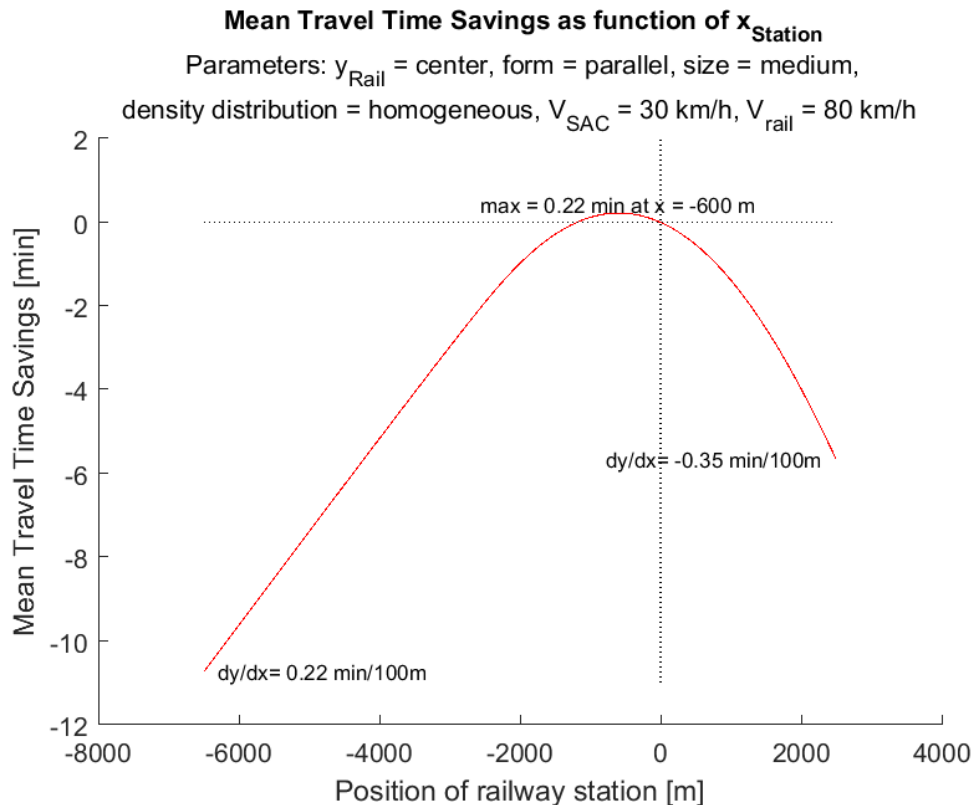
Figure 33: Travel Time Savings as one-dimensional function of station location (case 1.0)

3. **The higher the speeds of the feeders compared to rail, the lower the additional travel time savings through the second station.** This is somehow expectable. The more similar the speeds of rail and feeder, the less it makes sense to establish new stations, as travel time savings can also be achieved for stations further away from the centre of the town (with the hypothetical single station).

4. **The further outside the railway line, the lower the additional travel time savings through the second station.** The second station is only useful if the distances on the feeder are short. A setting where the railway line is anyway located far outside the town centre is thus not prone to the establishment of a second station.

5. **The higher the line density of the bus network, the lower the additional travel time savings through the second station.** This means that higher line density thanks to autonomous buses on the feeder on the one hand and additional train stops on the other hand do not make sense together. A combination of the two is inefficient.

6.3.2 Cancelling the station of towns

The assessment whether the cancellation of a station in a given situation is meaningful from the travel time point of view can be done as shown in Figure 34.

Based on the curve providing the mean travel time savings as a function of the station location, one draws the horizontal line at -2 minutes of travel time savings (i.e. 2 min of travel time loss per additional stop). This value is subsequently referred to as T_{limit}. If the nearest station

downstream, which would be used by the passengers of the station to be cancelled, features a travel time saving larger than -2 min, the cancellation is appropriate from a travel time point of view. In the example shown in Figure 34, the location which marks the boundary between the appropriate and the inappropriate station location (i.e. the horizontal coordinate of the point where the horizontal line intersects the travel time savings function) would be at around -7000 m. **We call this value the break-even location for cancellation**. If the nearest railway station were located less than 7000 m away from the town centre, the cancellation would make sense. If the nearest station were further away, the cancellation would not be advisable from the travel time point of view.

In other words, if stations and towns on a line are regularly spaced and the distance in between them is – in absolute values – lower than the break-even for cancellation, than it is beneficial in terms of travel times to cancel every second station.
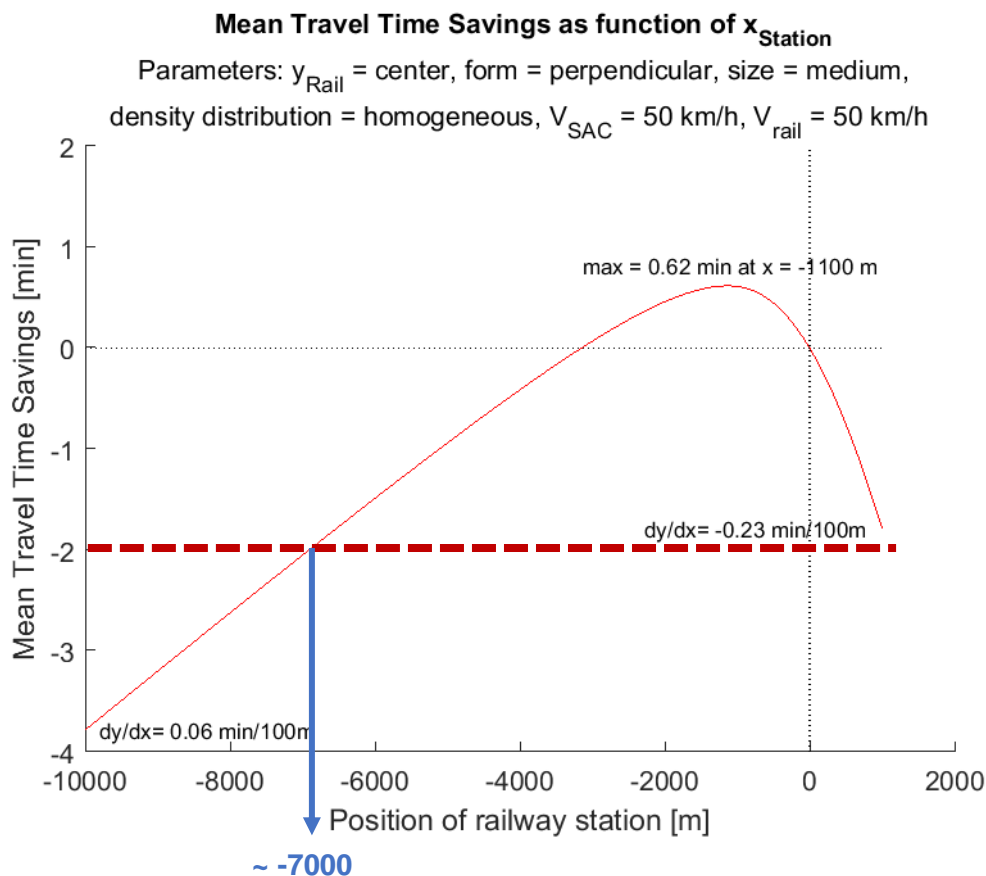
Figure 34: Cancelling the station of a town for case 10.2

The location of the break-even for cancellation obviously depends on the relative speeds of rail and feeder. Figure 34 is based on the scenario with lower train speeds (50 km/h) and high feeder speeds (50 km/h). Thus the break-even is located far away from the town centre. If we repeat the same procedure *ceteris paribus* for the other speed scenario (rail 80 km/h, car 30 km/h), we obtain the result in Figure 35. The break-even is now located at -2000 m, which is significantly closer to the town centre than before. The explained procedure can be applied fully identically to the bus feeder scenarios.
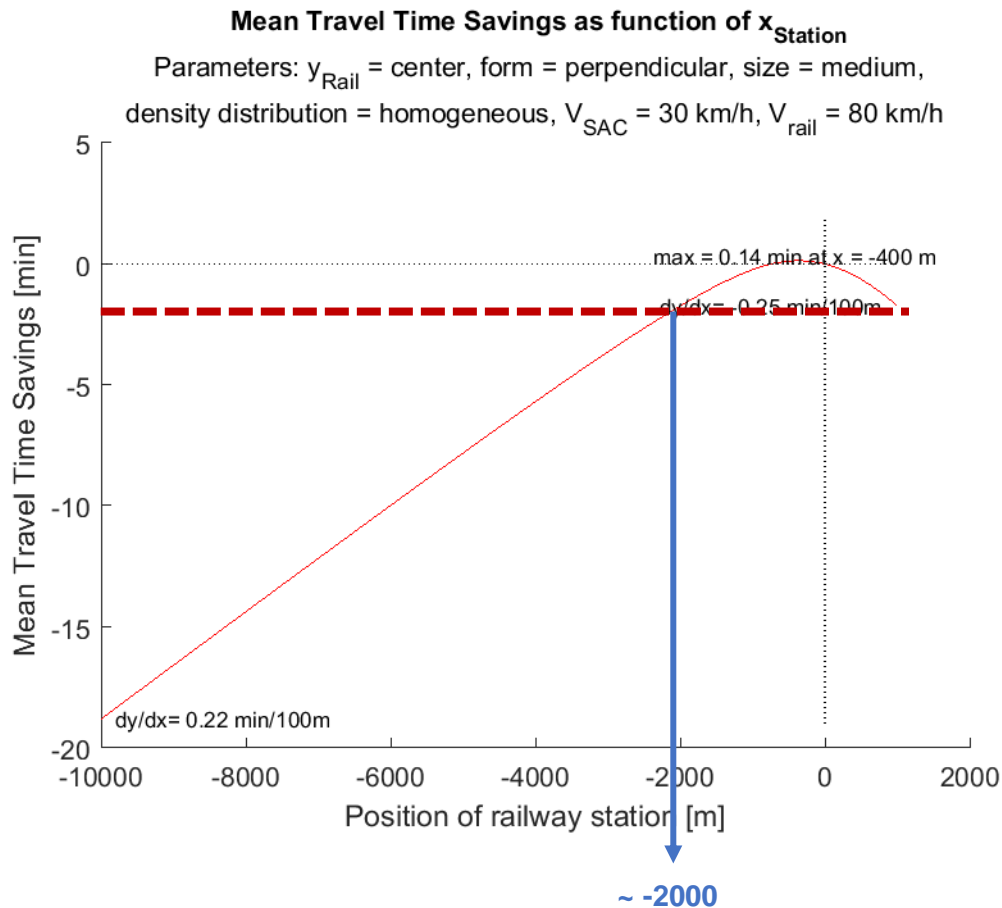
Figure 35: Cancelling the station of a town for case 2.0

Table 10 compares the break-even locations for cancellation of the different generic test cases. The conclusions of this comparison are very similar to those of the optimal station location:

- The break-even location for cancellation of car-based feeders is always left of the one for bus-based feeders (except setting circular-centre for the reason outlined in section 6.2.2 regarding the consolidation of the bus network).

- The more similar the speeds of the feeders and the railway, the higher the differences in terms of break-even location for cancellation between car-based feeder and bus-based feeder.

- The further outside the railway line of the town, the further left the break-even location for cancellation (equally valid for both types of feeder systems). Also, the further outside the railway line compared to the town, the higher the differences between car-based feeder and bus-based feeder, as the car-based feeder reacts more sensitively than the bus-based feeder.

- The high influence of speed is confirmed, both for car-based feeders as well as bus-based feeders. It is, however, much higher for car-based feeders than for bus-based feeders. Moreover, the influence of relative speed increases the further outside the railway line is located in respect to the town centre. Finally, the influence of speed is also higher for parallel and perpendicular towns than for purely circular ones.

Table 10: Locations of break-even for cancellation for generic test cases

Form	Case	v_Rail = 80 km/h, v_SAC = 30 km/h, v_bus = 20 km/h		v_Rail = 50 km/h, v_SAC = 50 km/h, v_bus = 30 km/h		Case
		Location of break-even for cancellation of station in [m] with respect to town centre				
		Car	**Bus**	**Car**	**Bus**	
Circ.	0.0	-1700	-1800	< -5000	-3300	9.0
Circ.	0.1	-1400	-1200	< -2500	-2300	9.1
Circ.	0.2	-1600	-1600			
Circ.	0.3	-2300	-2200	-6800	-4000	9.2
Para.	1.0	-2600	-1700	< -6500	-3400	10.1
Para.	1.1	-1900	-1500			
Para.	1.2	-3300	-2300			
Perp.	2.0	-2200	-1400	-7000	-2600	10.2
Perp.	2.1	-1700	-1100			
Perp.	2.2	-2800	-1800			
Circ.	3.0	-2100	-1600	< -5000	-2900	11.1
Circ.	3.1	-1600	-1100			
Circ.	3.2	-2900	-2200			
Circ.	4.0	-2800	-2000	< -5000	-3700	11.2
Circ.	4.1	-2000	-1400			
Circ.	4.2	-4100	-3000			
Para.	5.0	-2800	-1900	< -6500	-3800	12.1
Para.	5.1	-3700	-2500			
Para.	6.0	-3200	-1700	< -6500	-4300	12.2
Para.	6.1	-2300	-1300			
Perp.	7.0	-2900	-1400	-10000	-2500	12.3
Perp.	7.1	-3900	-2200			
Perp.	8.0	-3600	-1900	< -10000	-3600	12.4
Perp.	8.1	-2600	-1400			

White-shaded lines: town of size 'medium'

Yellow-shaded lines: town of size 'small'

Red-shaded rows: town of size 'large'

There is however one major difference compared to the reaction of the optimal station location to variations of the input parameters: **the break-even location for cancellation does <u>not</u> proportionally scale up with the size of the town**. Instead, the effect of the town size is under-proportional. For the bus-based feeder in test cases 0 to 8, the break-even locations for cancellation are in a pretty similar order of magnitude independently of the town size: 1,5 – 3 km. This corresponds roughly to the current spacing of railway stations on the Swiss network.

Following the above findings, the stations most likely to be suitable for cancellation are thus located on railway lines with comparably low speeds, towns far away from the station and low current spacing between stations. In return, lines having a high spacing of stations already now are less suitable for possible cancellation. In the case studies in chapter 8 we will apply these findings to real situations.

7 Analytical Formulation of the Travel Time Savings

7.1 Assumptions

This chapter deals with the analytical formulation of the car travel time savings function as derived in equation (17). For the bus feeder system, an analytical formulation is not possible, as the network generation includes discontinuities that cannot be easily modelled. For the car feeder system, we furthermore need to make a few simplifying assumptions:

- The settlement density needs to be homogeneous. For the inhomogeneous case, only a numerical calculation is possible.

- The shape of the settlement area is assumed to be rectangular with length L and height h (see Figure 36). This does not fully correspond to the forms used for the generic test cases. It is, however, a suitable approximation. In general, each shape can be modelled through a combination of rectangles, in some cases of infinitesimal size.

- The settlement area is assumed to be always fully centred at the origin of the axis system. This assumption matches with the one of the generic test cases.

With these assumptions equation (17) can be simplified as follows:

$$T = \frac{-x_{Si}}{v_{rail}} + \frac{D_f}{v_{car}} \cdot \underbrace{\frac{\iint_{P \in A} d_{S0} \cdot dA}{A}}_{D_{S0}} - \frac{D_f}{v_{car}} \cdot \underbrace{\frac{\iint_{P \in A} d_{Si} \cdot dA}{A}}_{D_{Si}} \qquad (25)$$
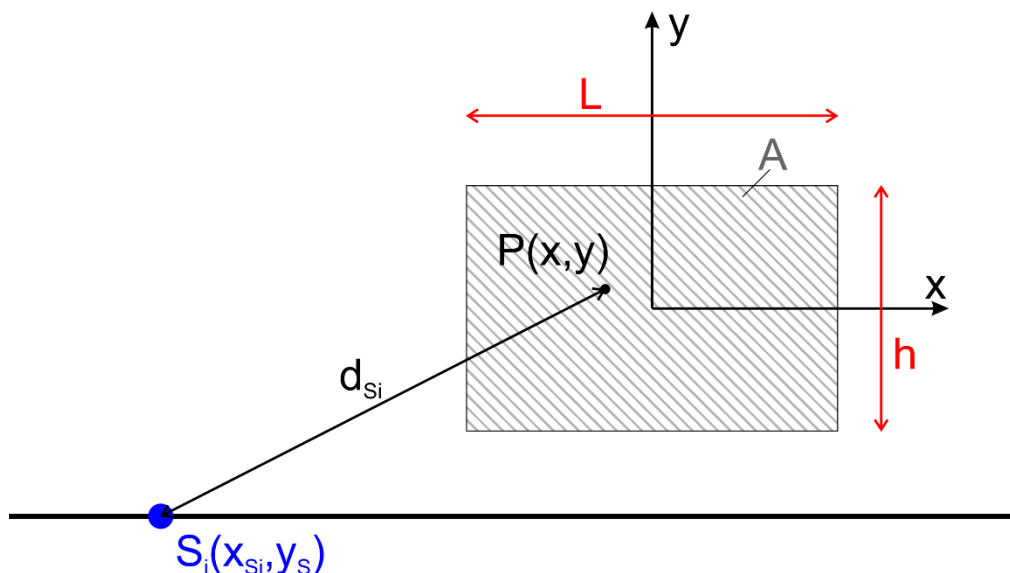
Figure 36: Concept of Analytical Model

7.2   Formulation

7.2.1 The Travel Time Savings function

d_{Si} being the distance between a point on the railway line and a point in the settlement area, we further obtain:

$$
T = \frac{-x_{Si}}{v_{rail}} + \frac{D_f}{v_{car} \cdot A}
$$

$$
\cdot \left(\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sqrt{x^2 + (y - y_s)^2}\, dx\, dy - \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sqrt{(x - x_{Si})^2 + (y - y_s)^2}\, dx\, dy \right) \tag{26}
$$

The first integral is a special case of the second one. We thus need to find a formulation of the latter being the more general form. Computing this integration, we get:

$$
\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sqrt{(x - x_{Si})^2 + (y - y_s)^2}\, dx\, dy = D_{Si}(x_{Si}, y_S, L, h)
$$

$$
= I\left(-x_{Si} + \frac{L}{2}, -y_S + \frac{h}{2}\right) + I\left(-x_{Si} - \frac{L}{2}, -y_S - \frac{h}{2}\right)
$$

$$
- I\left(-x_{Si} + \frac{L}{2}, -y_S - \frac{h}{2}\right) - I\left(-x_{Si} - \frac{L}{2}, -y_S + \frac{h}{2}\right) \tag{27}
$$

Where

$$
I(x, y) = \frac{xy}{3}\sqrt{x^2 + y^2} + \frac{y^3}{6}\ln\left(\sqrt{x^2 + y^2} + x\right) + \frac{x^3}{6}\ln\left(\sqrt{x^2 + y^2} + y\right) \tag{28}
$$

The first integral of equation (26) can be obtained by filling in $x_{Si} = 0$ into (27).

7.2.2 The first derivative of the Travel Time Savings function

The first derivative of T (as defined by equation (26)) after x_{Si} yields:

$$
\frac{\partial}{\partial x_{Si}} T = \frac{-1}{v_{rail}} - \frac{D_f}{v_{car} \cdot A} \cdot \frac{\partial}{\partial x_{Si}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sqrt{(x - x_{Si})^2 + (y - y_s)^2}\, dx\, dy \tag{29}
$$

Furthermore, we can put:

$$\frac{\partial}{\partial x_{Si}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sqrt{(x - x_{Si})^2 + (y - y_s)^2} \, dx \, dy = -\Gamma(x_{Si}, y_S, L, h)$$

$$= -\frac{\partial I}{\partial x}\left(-x_{Si} + \frac{L}{2}, -y_S + \frac{h}{2}\right) - \frac{\partial I}{\partial x}\left(-x_{Si} - \frac{L}{2}, -y_S - \frac{h}{2}\right)$$

$$+ \frac{\partial I}{\partial x}\left(-x_{Si} + \frac{L}{2}, -y_S - \frac{h}{2}\right) + \frac{\partial I}{\partial x}\left(-x_{Si} - \frac{L}{2}, -y_S + \frac{h}{2}\right)$$

(30)

Where

$$\frac{\partial I}{\partial x}(x, y) = \frac{y}{2}\sqrt{x^2 + y^2} + \frac{x^2}{2} \ln\left(\sqrt{x^2 + y^2} + y\right) + \frac{x^2}{6}$$

(31)

Combining (27) and (30), we also get:

$$\Gamma(x_{Si}, y_S, L, h) = -\frac{\partial}{\partial x_{Si}} D_{Si}(x_{Si}, y_S, L, h)$$

(32)

7.2.2.1   Finding the optimal station location

The optimal station location can be found by searching the x_{Si} where the first derivative of T is equal to zero. Thus, using equations (29) and (30):

$$\frac{\partial}{\partial x_{Si}} T = 0$$

$$\Leftrightarrow \frac{-1}{v_{rail}} - \frac{D_f}{v_{car} \cdot A} \cdot \left(-\Gamma(x_{Tmax}, y_S, L, h)\right) = 0$$

$$\Leftrightarrow \Gamma(x_{Tmax}, y_S, L, h) \cdot \frac{D_f}{v_{car} \cdot A} = \frac{1}{v_{rail}}$$

(33)

$$\Leftrightarrow \Gamma(x_{Tmax}, y_S, L, h) = \frac{v_{car} \cdot A}{v_{rail} \cdot D_f}$$

We can further define:

$$R_v = \frac{v_{car}}{v_{rail} \cdot D_f}$$

(34)

Which yields:

$$\Gamma(x_{Tmax}, y_S, L, h) = R_v \cdot A$$

$$\Leftrightarrow \frac{1}{A} \cdot \Gamma(x_{Tmax}, y_S, L, h) = R_v$$

(35)

If we put

$$L = h \cdot \lambda \Longleftrightarrow \lambda = \frac{L}{h} \tag{36}$$

it can be shown that the left member of equation (35) depends only on $\frac{x_{Tmax}}{L}$, $\frac{y_S}{h}$ and λ. This confirms our previous empirical finding that the optimal location of the station indeed scales together with the town size (if its form as well as the relative position of the railway line expressed by λ and $\frac{y_S}{h}$ respectively remain unchanged). It is thus possible to calculate $\frac{x_{Tmax}}{L}$ when knowing $\frac{y_S}{h}$, λ and R_v.

Using these findings and the same approach for the maximum travel savings, equation (26) can be transformed to read as follows for $x_{Si} = x_{Tmax}$:

$$\frac{T_{max} \cdot v_{rail}}{L} = \frac{-x_{Tmax}}{L} + \frac{1}{R_v} \cdot \left(\frac{D_{S0}(0, y_S, L, h)}{A \cdot L} - \frac{D_{Smax}(x_{Tmax}, y_S, L, h)}{A \cdot L} \right) \tag{37}$$

The terms $\frac{D_{Smax}}{A \cdot L}$ and $\frac{D_{S0}}{A \cdot L}$ do only depend on $\frac{y_S}{h}$, λ and $\frac{x_{Tmax}}{L}$. Knowing the first two as well as R_v, we can compute $\frac{x_{Tmax}}{L}$ through equation (35) and thus also $\frac{T_{max} \cdot v_{rail}}{L}$.

7.2.2.2   Slope of the travel time savings function on the edges of the domain

The slope of the travel time savings function is given by its first derivative. Here we are especially interested in the slope when x_{Si} tends to plus or minus infinity.

In a first step, we can calculate the limit of $\Gamma(x_{Si}, y_S, L, h)$:

$$\lim_{x_{Si} \to -\infty} \Gamma(x_{Si}, y_S, L, h) = L \cdot h$$

$$\lim_{x_{Si} \to +\infty} \Gamma(x_{Si}, y_S, L, h) = -L \cdot h \tag{38}$$

The mathematical proof of both limits is not trivial and is left to the interested reader.

Hence we obtain:

$$\lim_{x_{Si} \to -\infty} \frac{\partial}{\partial x_{Si}} T = \lim_{x_{Si} \to -\infty} \frac{-1}{v_{rail}} + \frac{D_f}{v_{car} \cdot A} \cdot \Gamma(x_{Si}, y_S, L, h)$$

$$= \frac{-1}{v_{rail}} + \frac{D_f}{v_{car} \cdot A} \cdot L \cdot h = \frac{-1}{v_{rail}} + \frac{D_f}{v_{car}} \tag{39}$$

And analogously:

$$\lim_{x_{Si} \to +\infty} \frac{\partial}{\partial x_{Si}} T = \frac{-1}{v_{rail}} + \frac{D_f}{v_{car} \cdot A} \cdot (-L \cdot h) = \frac{-1}{v_{rail}} - \frac{D_f}{v_{car}} \tag{40}$$

Both limits can be verified empirically. If we fill in the values of case 1.0 for instance, we obtain:

$$\lim_{x_{Si} \to +\infty} \frac{\partial}{\partial x_{Si}} T = \frac{-1}{v_{rail}} - \frac{D_f}{v_{car}} = \frac{-1}{80\frac{km}{h}} - \frac{1,5}{30\frac{km}{h}} = -0,0625\frac{h}{km} = -0,375\frac{min}{100m}$$

(41)

$$\lim_{x_{Si} \to -\infty} \frac{\partial}{\partial x_{Si}} T = \frac{-1}{v_{rail}} - \frac{D_f}{v_{car}} = \frac{-1}{80\frac{km}{h}} + \frac{1,5}{30\frac{km}{h}} = 0,0375\frac{h}{km} = 0,225\frac{min}{100m}$$

Both values match well with the empirically determined ones given in Figure 33 (page 50).

7.2.3 Calculation of the break-even for cancellation

The calculation of the break-even location for calculation labelled x_{Tlimit} is defined as follows:

$$T(x_{Tlimit}) = T_{limit}$$

$$\Leftrightarrow -\frac{x_{Tlimit}}{v_{rail}} + \frac{D_f}{v_{car} \cdot A}\left(D_{S0}(0, y_S, L, h) - D_{Si}(x_{Si}, y_S, L, h)\right) = T_{limit}$$

(42)

$$\Leftrightarrow -\frac{x_{Tlimit}}{L} + \frac{v_{rail} \cdot D_f}{v_{car} \cdot A \cdot L}\left(D_{S0}(0, y_S, L, h) - D_{Si}(x_{Tlimit}, y_S, L, h)\right) = \frac{T_{limit} \cdot v_{rail}}{L}$$

If we put:

$$K = \frac{T_{limit} \cdot v_{rail}}{L}$$

(43)

And insert equation (34) into (42), we obtain:

$$-\frac{x_{Tlimit}}{L} + \frac{1}{R_v \cdot A \cdot L}\left(D_{S0}(0, y_S, L, h) - D_{Slimit}(x_{Tlimit}, y_S, L, h)\right) = K$$

(44)

While the terms $\frac{D_{Slimit}}{A \cdot L}$ and $\frac{D_{S0}}{A \cdot L}$ like in equation (37) do only depend on $\frac{y_S}{h}$, λ and $\frac{x_{Tlimit}}{L}$, the calculation of $\frac{x_{Tlimit}}{L}$ such that the above equation is fulfilled also depends on K and R_v. There is one additional parameter compared to equation (37).

7.3 Application

7.3.1 Application to generic test cases

The analytical formulas derived above have been applied to all generic test of the car-based feeder system operating in a settlement of <u>homogeneous density</u>. **The non-rectangular shapes of the generic test cases have been approximated by rectangles of same area and same ratio of length to height** (i.e. same λ as defined by equation (36)).

Table 11 provides an overview of the comparison by indicating the following information:

- Both the empirically and analytically determined maximum travel savings denoted as T_{max} together with their relative deviation.

- The standard deviation of the empirical and analytical values over the domain of interest (see Table 5)

- Both the empirically and analytically determined optimal location, denoted as x_{Tmax}.

We notice that the deviations between the empirical and analytical values of the maximum travel time savings are very small. The modelling of the round shape by a rectangle of same area and proportions was thus a suitable approximation. The deviations between the optimal station locations are a bit larger, but this is primarily due to the resolution of the experimental model with steps of 100 m.

Figure 37, Figure 38 as well as Figure 39 show the travel time savings functions for all generic test cases of medium-sized towns with homogeneous settlement density (corresponding to the generic test cases listed in Table 11 with white-shaded lines): for all three positions of the railway line that were investigated (centre, tangent, outlier) as well as both speed combinations. We notice that for a given town form, the position of the railway line matters far less than the chosen speed combinations.
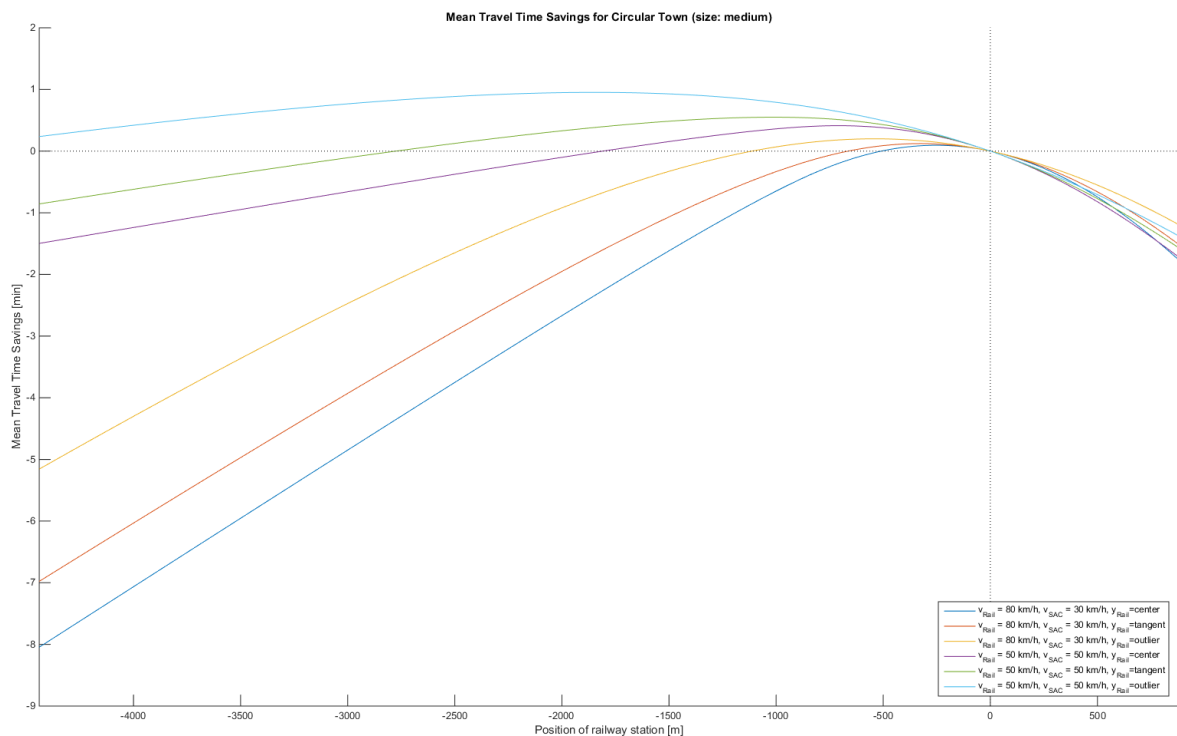
Figure 37: Summary of travel time functions for medium-sized circular towns

Table 11: Comparison of empirical results to analytical calculations

Case	T_{max} [min] *empirical*	T_{max} [min] *analytical*	difference	σ_T [min] (over domain of interest as defined in Table 3)	x_{Tmax} [m] *empirical*	x_{Tmax} [m] *analytical*
0.0	0.0908	0.0945	3.9%	0.020	-300	-253
0.1	0.0451	0.0473	4.7%	0.010	-100	-126
1.0	0.2223	0.2300	3.3%	0.069	-600	-614
1.1	0.1319	0.1380	4.4%	0.038	-400	-368
2.0	0.1364	0.1369	0.4%	0.055	-400	-367
2.1	0.0751	0.0750	0.1%	0.029	-200	-202
3.0	0.1118	0.1219	8.3%	0.030	-300	-327
3.1	0.0503	0.0610	17.5%	0.015	-200	-164
4.0	0.1961	0.1995	1.7%	0.008	-500	-540
4.1	0.0970	0.0997	2.7%	0.004	-300	-270
5.0	0.2375	0.2466	3.7%	0.071	-600	-659
6.0	0.2849	0.2931	2.8%	0.048	-800	-786
6.1	0.1608	0.1657	3.0%	0.027	-400	-444
7.0	0.1945	0.2043	4.8%	0.005	-500	-552
8.0	0.2990	0.2994	0.1%	0.009	-800	-815
8.1	0.1632	0.1649	1.0%	0.006	-500	-450
9.0	0.4132	0.4122	0.2%	0.012	-700	-709
9.1	0.2042	0.2061	0.9%	0.006	-400	-355
10.1	0.9584	0.9875	2.9%	0.041	-1600	-1662
10.2	0.6166	0.6183	0.3%	0.033	-1100	-1155
11.1	0.5288	0.5501	3.9%	0.018	-1000	-1013
11.2	0.9463	0.9519	0.6%	0.005	-1800	-1848
12.1	1.0347	1.0713	3.4%	0.043	-1800	-1834
12.2	1.2867	1.3155	2.2%	0.029	-2300	-2369
12.3	1.0193	1.0189	0.0%	0.003	-2200	-2148
12.4	1.5021	1.4963	0.4%	0.005	-3100	-3048
Ø	/	/	3.0%	0.0246 min = 1.5 s	/	/

White-shaded lines: town of size 'medium'

Grey-shaded lines: town of size 'small'
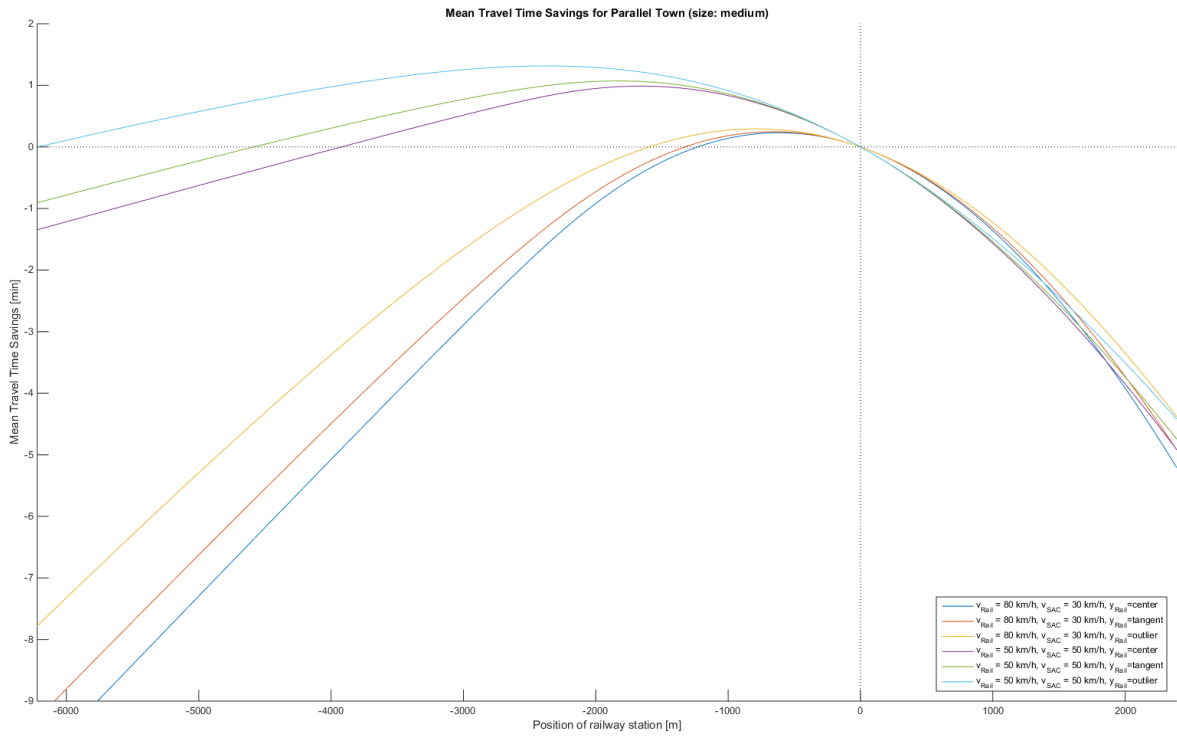
Figure 38: Summary of travel time functions for medium-sized parallel towns
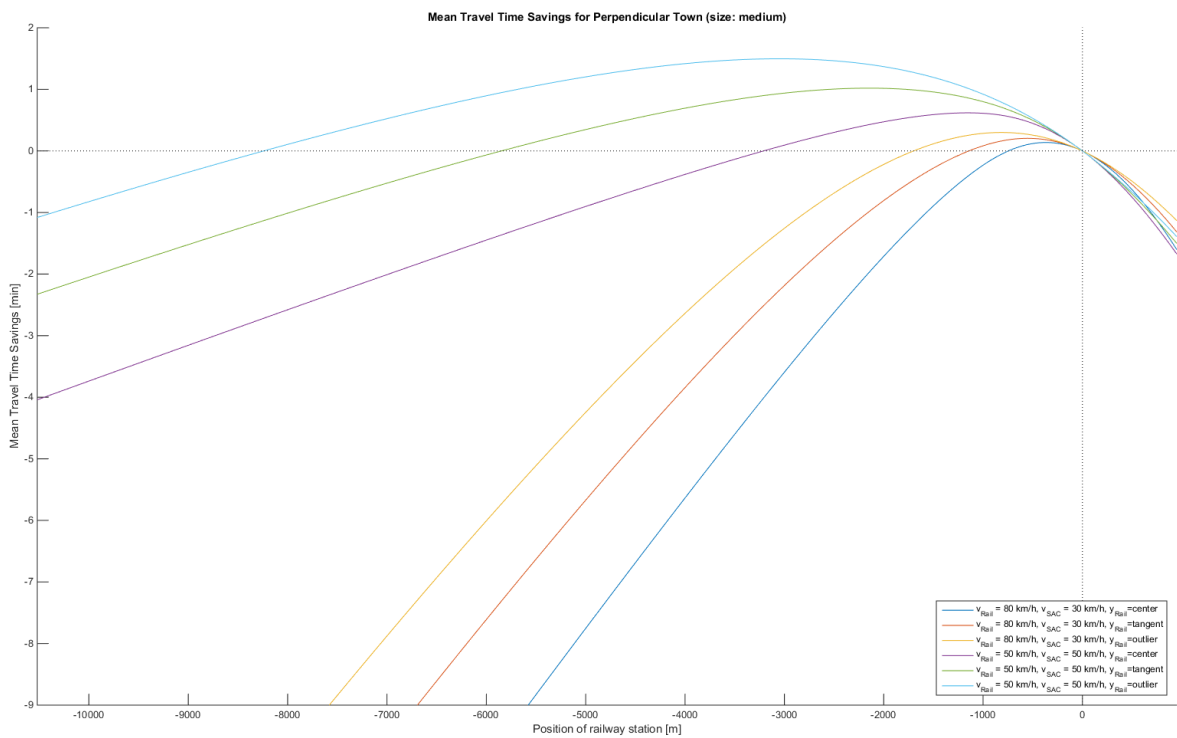
Figure 39: Summary of travel time functions for medium-sized perpendicular towns

7.3.2 Dimensionless nomograms

On the basis of equation (35), we found that the ratio of the optimal station location to the length of the town $\frac{x_{Tmax}}{L}$ does only depend on R_v, λ and $\frac{y_S}{h}$. We can use this finding to establish a series of dimensionless nomograms which allow computation of $\frac{x_{Tmax}}{L}$ when knowing R_v, λ and $\frac{y_S}{h}$. They can be found in Appendix A2.
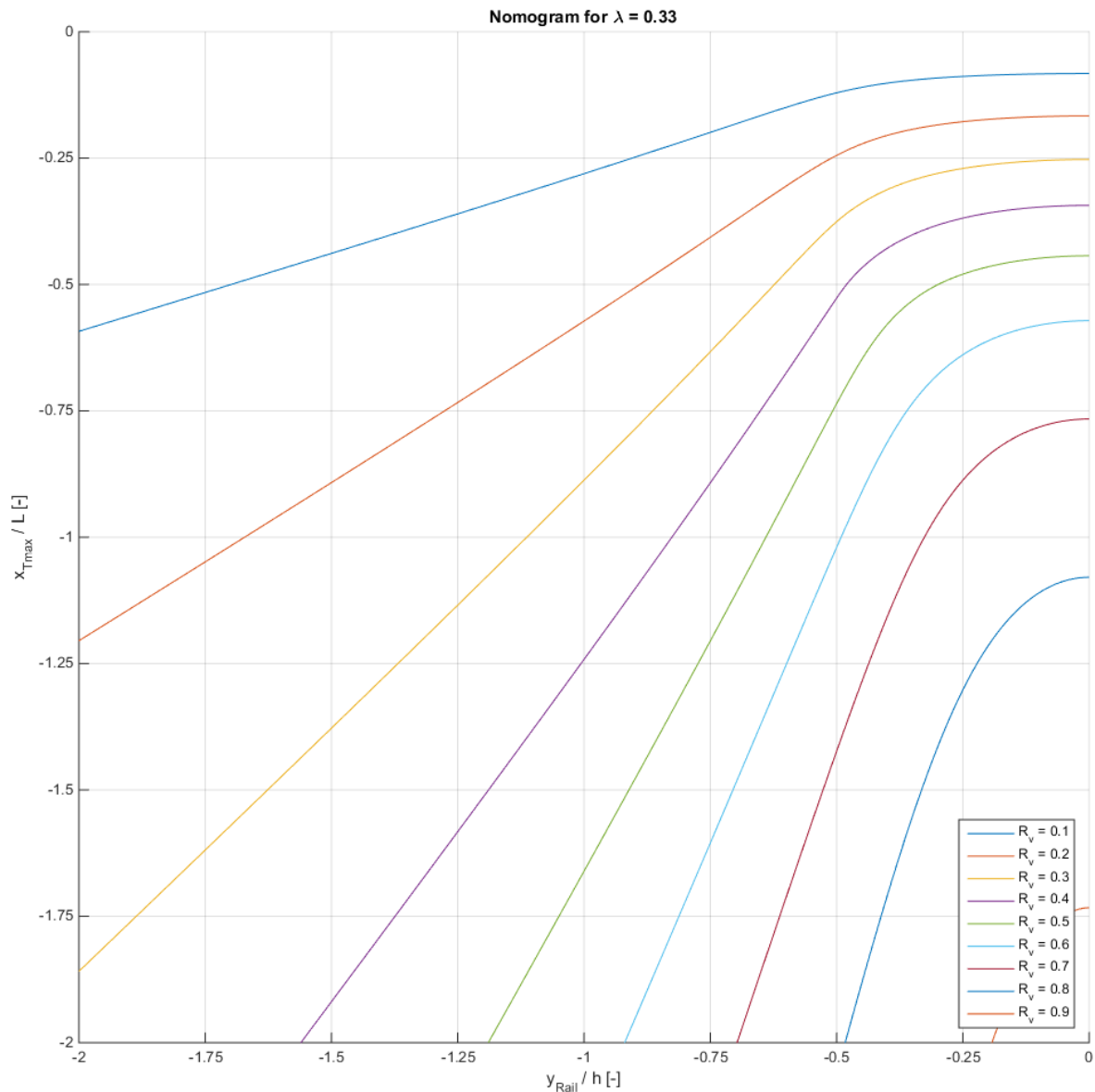
Figure 40: Example of nomogram for optimal station location

Figure 40 shows one example of the nomograms (for $\lambda = 0.33$). Based on these we can confirm the findings we already got from the empirical simulations of the generic test cases:

- The more similar the speeds of rail and car-based feeder, the further left the optimal station location: curves with a higher R_v have lower $\frac{x_{Tmax}}{L}$ values.

- The further outside the railway line from the town centre, the further left the optimal station location: $\frac{x_{Tmax}}{L}$ increases in absolute terms with a higher absolute value of $\frac{y_S}{h}$.

- The further outside the railway line, the greater the importance of the speed ratio. This means that towns with railway lines not passing through their centre show less robustness when it comes to the optimal station location. Small changes in relative speeds can have a greater impact than if the railway line passing centrally through the town. This is can be seen through the growing gap between the curves in the direction of increasing absolute values of $\frac{y_S}{h}$.

Furthermore, when applying the same approach, we can also establish similar dimensionless nomograms for the maximum achievable travel time savings. They are given in Appendix A3.

Figure 41 shows an example of them (for $\lambda = 0.33$). We notice that the absolute value of the achievable travel time savings scales up together with the size of town (at constant λ). Furthermore, it does not only depend on the ratio of speeds, but also on the absolute value of them. The higher the speeds (at constant ratio), the lower the resulting travel time savings. Similarly, we can confirm several findings from the experimental generic test cases: The further outside the railway line from the town, the higher the travel time savings and the greater the impact of the speed ratio.
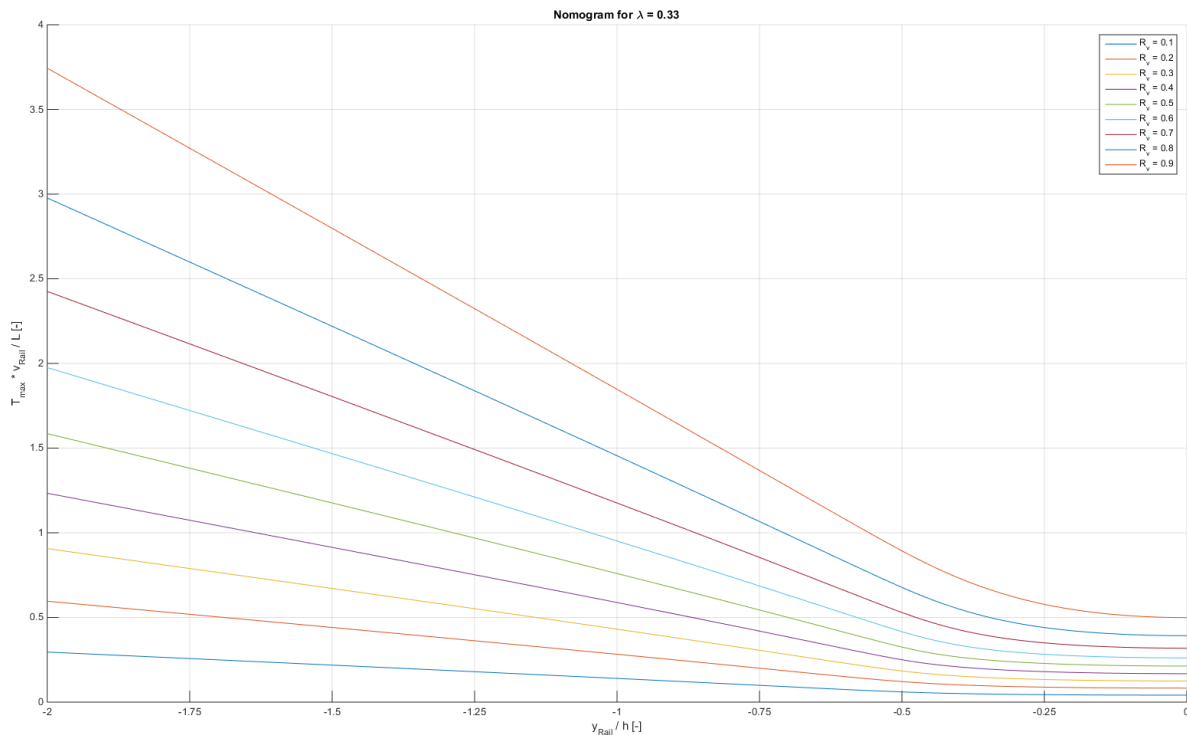
Figure 41: Example of nomogram for maximum travel time savings

It is mathematically possible to establish similar nomograms for the calculation of the break-even location for cancellation x_{Tlimit}. Unlike the previous nomograms, which have all three parameters (R_v, λ and $\frac{y_S}{h}$) for one output ($\frac{x_{Tmax}}{L}$, respectively $\frac{T_{max} \cdot v_{rail}}{L}$), these take four parameters (the previous three plus K as defined in equation (43)) for one output. This makes it much more difficult to represent these nomograms in a meaningful way. In fact, for given λ and R_v, the result is not anymore a curve, but a surface in space, which cannot be easily represented on a sheet of paper. For a complete set, we would not only need a series of nomograms for each λ, but one nomogram for every possible combination of λ and one additional parameter (for instance K).

We will therefore only provide the nomograms for the combinations of λ and K that are relevant for some of the theoretical test cases we have investigated. The corresponding values are given in Table 12. The nomograms are attached in Appendix A4. Further nomograms for different values of λ and K can be constructed using equation (44).

Table 12: λ and K values of considered test cases

Relevant Cases	Form	T_{limit}	v_{rail}	L	λ	K
0 / 3.0 / 4.0	Circle			1772 m	1	-1,505
1.0 / 5.0 / 6.0	Parallel		80 km/h	4781 m	2,5	-0,558
2.0 / 7.0 / 8.0	Perpendicular	- 2 min		1912 m	0,4	-1,395
9.0 / 11.1 / 11.2	Circle			1772 m	1	-0,941
10.1 / 12.1 / 12.2	Parallel		50 km/h	4781 m	2,5	-0,349
10.2 / 12.3 / 12.4	Perpendicular			1912 m	0,4	-0,872

7.4 Limitations

The analytical formulation of the travel time savings function, and subsequently the optimal station location as well as the break-even location for cancellation, can only be applied to continuous feeder systems travelling at constant speed. Furthermore, the settlement density is required to be homogeneous over the entire town. Inhomogeneous settlement areas could possibly be approximated through reduced areas, but this requires further research and is first and foremost dependent on the specific inhomogeneity at hand.

The general principles that could be found through the dimensionless nomograms remain qualitatively valid for towns with inhomogeneous density or bus-based-feeder systems. For quantitative conclusions, a simulation with the precise input data is required.

8 Case Studies

Together with SBB, three case study corridors were decided:

- Lenzburg (excluded) – Rotkreuz (excluded) (Freiamt)

- Winterthur (excluded) – Wil

- Glarus (excluded) - Linthal

8.1 Input data

8.1.1 Form of the settlements

First of all, the forms of the settlements in the respective corridors needed to be identified and quantified so as to fit the requirements of the calculation model. The parameters R und L as specified in Table 3 and Table 5 were measured on a map. Settlements needed to be approximated by either a circular or a lengthy shape (of an orientation to be measured too). Areas inside this shape where there is no settlement are taken into account by using a settlement density to 0 (see below). The Swiss national coordinate system (Landeskoordinaten) was used to locate the towns.

8.1.2 Settlement density

The number of inhabitants per hectare was retrieved from a dataset by Federal Office for Statistics (Bundesamt für Statistik (BfS), 2017). Before being able to use it as input to the previously developed code, it needed to be converted to the required format. Most importantly, the resolution (one data point per hectare) was not sufficient. Figure 42 shows an example of the raw data as it is given by the dataset from BfS. The data points are placed on a grid of 100 m x 100 x. Figure 43 shows the output after processing. The data points have been placed on a grid of 10 m x 10 m (approximated in the circular parts of the town shape). The processing was done following the subsequent procedure:

1. The density function was modelled by piecewise cubic splines in space. For each square of 100 m x 100 m around one raw data point, the density was assumed to be a function of the form:

$$\delta_i(x, y) = a_i \cdot x^3 + b_i \cdot x^2 y + c_i \cdot xy^2 + d_i \cdot y^3$$
$$+ e_i \cdot x^2 + f_i \cdot xy + g_i \cdot y^2 + h_i \cdot x + k_i \cdot y + m_i \tag{45}$$

Where x and y are normalized coordinates varying in an interval $[0; l]$. The parameter l is determined such as to minimize the error of the overdetermined system of equations that needs to be solved to calculate the coefficients $a_i \dots m_i$ (see below).
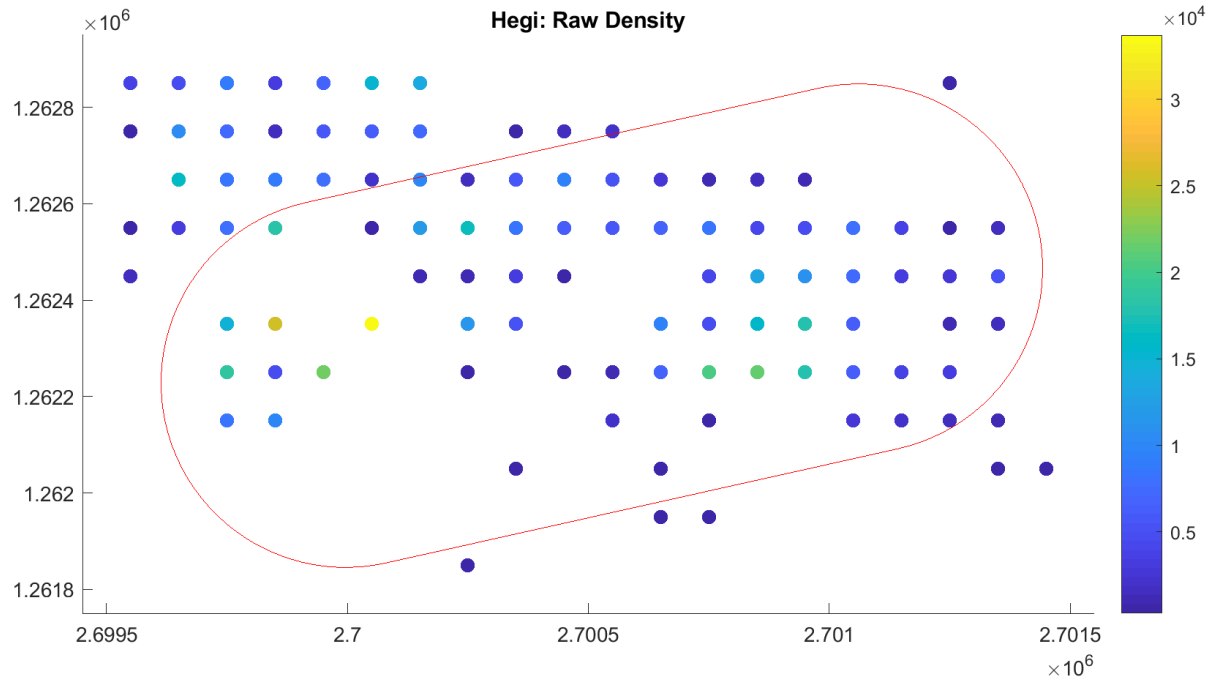
Figure 42: Raw density for the settlement area of Winterthur Hegi
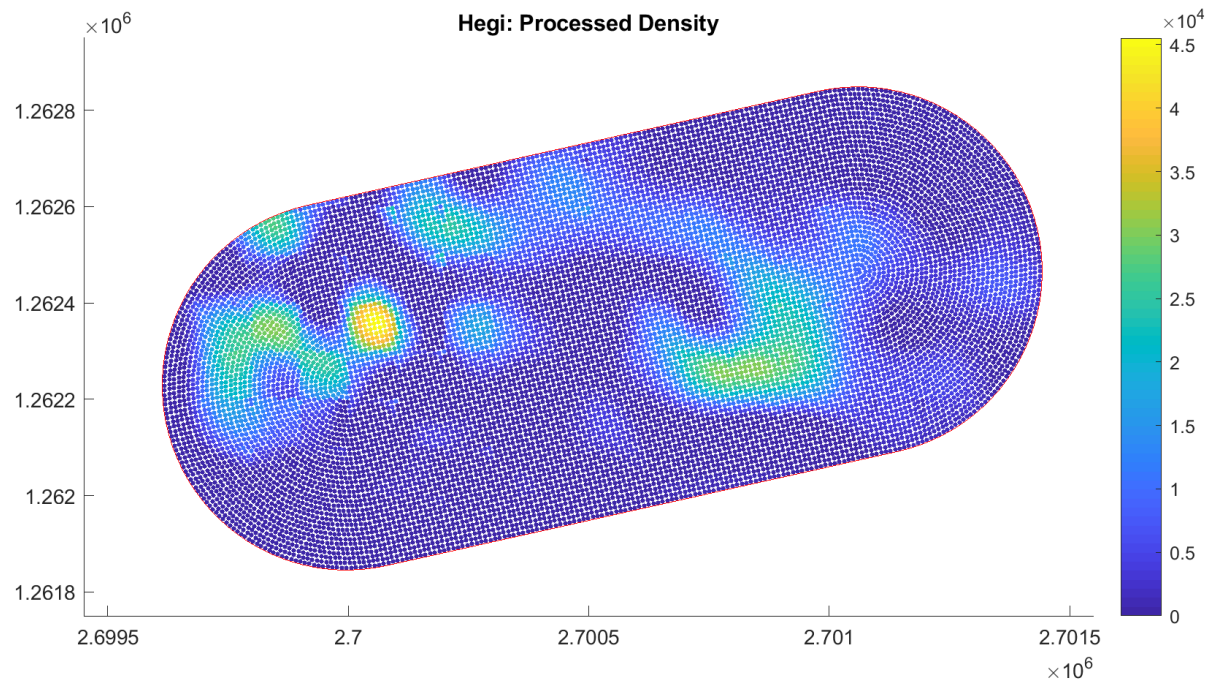
Figure 43: Processed density for the settlement area of Winterthur Hegi

2. The integral of the density function over the square of side length l around the raw data point of D_i inhabitants in the respective square is thus:

$$\iint\limits_0^l \delta_i(x,y)dxdy = a_i \cdot \frac{l^5}{4} + b_i \cdot \frac{l^5}{6} + c_i \cdot \frac{l^5}{6} + d_i \cdot \frac{l^5}{4}$$

$$+ e_i \cdot \frac{l^4}{3} + f_i \cdot \frac{l^4}{4} + g_i \cdot \frac{l^4}{3} + h_i \cdot \frac{l^3}{2} + k_i \cdot \frac{l^3}{2} + m_i \cdot l^2 = D_i \qquad (46)$$

$$\Leftrightarrow a_i \cdot \frac{l^3}{4} + b_i \cdot \frac{l^3}{6} + c_i \cdot \frac{l^3}{6} + d_i \cdot \frac{l^3}{4}$$

$$+ e_i \cdot \frac{l^2}{3} + f_i \cdot \frac{l^2}{4} + g_i \cdot \frac{l^2}{3} + h_i \cdot \frac{l}{2} + k_i \cdot \frac{l}{2} + m_i = \frac{D_i}{l^2}$$

3. Furthermore, we request the cubic splines to be continuously differentiable at the edges of the squares. Continuity in x-direction is given by:

$$f_i(x=0) = f_{i-1}(x=l)$$

$$\Leftrightarrow \begin{cases} d_i = d_{i-1} \\ g_i = g_{i-1} + c_{i-1} \cdot l \\ k_i = k_{i-1} + f_{i-1} \cdot l + b_{i-1} \cdot l^2 \\ m_i = m_{i-1} + h_{i-1} \cdot l + e_{i-1} \cdot l^2 + a_{i-1} \cdot l^3 \end{cases}$$

$$\frac{\partial}{\partial x} f_i(x=0) = \frac{\partial}{\partial x} f_{i-1}(x=l)$$

$$\Leftrightarrow \begin{cases} c_i = c_{i-1} \\ f_i = f_{i-1} + 2b_{i-1} \cdot l \\ h_i = h_{i-1} + 2e_{i-1} \cdot l + 3a_{i-1} \cdot l^2 \end{cases} \qquad (47)$$

Continuity in y-direction (where t is the number of squares in x-direction) is given by:

$$f_i(y=0) = f_{i-t}(y=l)$$

$$\Leftrightarrow \begin{cases} a_i = a_{i-t} \\ e_i = e_{i-t} + b_{i-t} \cdot l \\ h_i = h_{i-t} + f_{i-t} \cdot l + c_{i-t} \cdot l^2 \\ m_i = m_{i-t} + k_{i-t} \cdot l + g_{i-t} \cdot l^2 + d_{i-t} \cdot l^3 \end{cases}$$

$$\frac{\partial}{\partial y} f_i(y=0) = \frac{\partial}{\partial y} f_{i-t}(y=l)$$

$$\Leftrightarrow \begin{cases} b_i = b_{i-t} \\ f_i = f_{i-t} + 2c_{i-t} \cdot l \\ k_i = k_{i-t} + 2g_{i-t} \cdot l + 3d_{i-t} \cdot l^2 \end{cases} \qquad (48)$$

4. If we have m squares in x-direction and n squares in y-direction, the total number of unknowns is $10 \cdot m \cdot n$. The number of equations is:

- $m \cdot n$ times equation (46)

- $n \cdot (m-1)$ times the set of 7 equations for continuity in x-direction (47)

- $m \cdot (n-1)$ times the set of 7 equations for continuity in y-direction (48)

5. The total number of equations is thus $15 \cdot m \cdot n - 7 \cdot (m+n)$. This number is larger than the number of unknowns for all combinations of $m, n \geq 3$ (which is in general the case for our purpose). The system of equations is thus overdetermined. There is no solution satisfying all equations.

   The above equations have been aggregated into matrix form. The coefficients $a_i \ldots m_i$ could then be determined numerically by MATLAB such that the overall error vector is minimal. This error vector depends again on the choice of l which steers how much weight is given to the continuity equations and how much weight is given to the integral. l has been chosen such that the standard deviation of the error vector divided by the mean absolute value of the error vector is minimal.

6. At the end, the settlement densities calculated through the cubic splines for each point on the 10 m x 10 m grid are normalized such that the sum of the inhabitants inside the red framed shape (see example in Figure 42 and Figure 43is the same for the processed densities than for the raw data.

8.1.3 Speeds

The top speeds on the railway line in the vicinity of a particular station have been determined through the RADN tables (SBB Infrastruktur, 2016). We assumed train category R and the highest braking performance. In case the current station is at the limit between two sections of different top speeds, the lower one of the two speeds was assumed (conservative assumption).

The car speeds have been determined from GoogleMaps. A sample of three different routes per town was considered. The bus speeds have been calculated as follows: we assume that the running speed is identical to the one of the car, but the bus stops on average 3 three per km for 20 seconds each. Hence the bus speeds is:

$$v_{bus} = \frac{1 \, km}{\frac{1 \, km}{v_{car}} + 1 \, min} \tag{49}$$

Table 13 provides the full list of speeds for all modes (car, bus, rail) and for all towns we will analyse in the following section.

8.1.4 Passenger frequencies

Passenger frequencies (of 2014) of the railway stations in the case study corridors have been retrieved from the SBB website (SBB Personenverkehr, 2014) (see Table 13). In this study we use a standard temporal distribution of demand as given by Weidmann (2011). The highest hourly demand occurs between 07:00 and 08:00 in the morning and makes up 22 % of the

total daily demand (Mo – Fr). The resulting peak hour frequencies (per direction) are also given in Table 13. They determine, among other factors, the space needs of the drop-off / boarding facility as well as of the storage area for autonomous cars.

Table 13: Speeds and passenger frequencies for case studies

	V_{bus} [km/h]	V_{car} [km/h]	V_{rail} [km/h]	Daily passenger frequencies (Mo-Fr) [boarding + alighting]	Peak passenger frequency (p/h/direction)
Lenzburg (excluded) – Rotkreuz (excluded)					
Hendschiken	21.8	16.0	115	450	50
Dottikon	27.9	19.0	125	1'600	176
Dintikon	28.5	19.3	125		
Wohlen	25.6	17.9	125	6'200	682
Boswil	32.0	20.9	125	880	97
Bünzen	32.5	21.1	125		
Muri	27.8	19.0	125	2'600	286
Benzenschwil	26.0	18.1	115	220	24
Mühlau	29.3	19.7	115	200	22
Sins	26.5	18.4	125	1'300	143
Oberrüti	30.3	20.1	115	350	39
Winterthur (excluded) – Wil					
Hegi	23.3	16.8	130	570	63
Räterschen	35.0	22.1	95	670	74
Schottikon	27.3	18.8	95	440	48
Elgg	27.6	18.9	125	1'800	198
Aadorf	30.7	20.3	115	2'000	220
Guntershausen	44.0	25.4	115	420	46
Eschlikon	31.2	20.5	115	1'400	154
Sirnach	26.8	18.5	115	820	90
Wil	22.7	16.5	105	22'400	2'464
Glarus (excluded) – Linthal					
Glarus	-	-	-	3'200	352
Ennenda	22.0	16.1	70	620	68
Mitlödi	28.0	19.1	80	360	40
Schwanden	32.7	21.2	80	1'500	165
Nidfurn	37.0	22.9	80	180	20
Haslen	26.5	18.4	80		
Leuggelbach	24.0	17.1	80	60	7
Luchsingen	30.5	20.2	80	410	45
Hätzingen	25.0	17.6	80		
Diesbach	29.3	19.7	80	130	14
Betschwanden	27.0	18.6	80		
Rüti GL	28.0	19.1	80	210	23
Linthal	27.5	18.9	60	350	39

8.1.5 Existing bus network

The number of bus lines which currently serve the towns under consideration have been determined based on the line maps by the regional fare communities (Tarif-/Verkehrsverbünde):

- Lenzburg – Rotkreuz: A-Welle

- Winterthur – Wil: ZVV and Ostwind

- Glarus – Linthal: Ostwind

8.1.6 Railway lines

Unlike in the generic test cases, the railway lines are not fully straight anymore. Their alignment has been modelled by using the Swiss national coordinate system (Landeskoordinaten). The location of the current station was determined likewise. Furthermore, data published by SBB Infrastruktur is used to determine the spacing between the stations (SBB Infrastruktur, 2013).

8.2 Application of the simulation environments to the case study towns

8.2.1 Overview of results

The results of applying the simulation environments 2a and 3a (see section 5.3.6) to the towns in the case study corridors are given in Table 14 (corridor Lenzburg – Rotkreuz), Table 15 (corridor Winterthur – Wil) and Table 16 (corridor Glarus – Linthal). The results highlighted in yellow are those that are worth further discussion in the next section 8.2.2.

8.2.1.1 Methodological remarks

- When calculating the break-even location for cancellation, 2 minutes is used for T_{limit} (i.e. the time loss per additional stop). With modern trains and/or low speeds on the railway line, the time loss per additional stop is likely to be less than 2 minutes. The travel time when not cancelling the station is thus overestimated. On the other side, the travel time when cancelling the station is also overestimated, as only one speed value is used for the feeder, both for in-town road sections and out-of-town road sections: namely the lower in-town speed. In a first approximation, one can expect both effects to compensate such that the obtained results for the break-even location for cancellation are in the correct order of magnitude.

- All considerations regarding the opportunity or non-opportunity of cancelling a railway station do only take into account the travel times of the specific town under analysis. They do **not** include travel time gains of upstream travelling passengers which save time due the train stopping once less. This requires information on patronage in the specific cross-section which was not available for the present research. If we took into account these travel time gains, we could qualitatively state that the further downstream

a station is located, the more passengers travel through its cross-section, the higher the likelihood that cancellation has overall positive effects.

- In the corridor Lenzburg – Rotkreuz, there is not only one main demand direction, but two. It is assumed that the demand splits up on the two directions inversely proportionally to the travel times to Lenzburg and Rotkreuz respectively. Under this assumption, the break-even is located in Muri where demand divides half-half on both directions. For the simulations, the towns situated north of Muri are calculated with demand oriented to/from Lenzburg, the ones south of Muri with demand oriented to/from Rotkreuz. Muri being exactly on the boundary, it is simulated from both directions.

Table 14: Results for corridor Lenzburg - Rotkreuz

Town	Feeder system	line density [-]	Optimal location [m]	Travel time savings	Break-even location for cancellation	Distance to next down-stream station [m]
Hendschiken	Car	-	771 m	1.39 min	- 590 m	3000 m
	Bus (new # lines)	1	771 m	1.91 min	- 445 m	
Dottikon	Car	-	- 312 m	0.34 min	- 1760 m	2720 m
	Bus (current # lines)	1	- 312 m	0.81 min	- 1040 m	
	Bus (new # lines)	2	- 312 m	0.81 min	- 1450 m	
Dintikon	Car	-	0 m	0 min	- 1450 m	
	Bus (current # lines)	1	0 m	0 min	- 1040 m	
	Bus (new # lines)	2	0 m	0 min	- 1040 m	
Wohlen	Car	-	0 m	0 min	- 1220 m	3870 m
	Bus (current # lines)	6	- 392 m	0.06 min	- 1115 m	
	Bus (new # lines)	9	206 m	0.20 min	- 1115 m	
Boswil	Car	-	299 m	0.15 min	- 1030 m	5960 m
	Bus (new # lines)	1	149 m	0.21 min	- 625 m	
Bünzen	Car	-	0 m	0 min	-2000 m	
	Bus (new # lines)	1	149 m	0.04 min	- 1140 m	
Muri (main demand direction to Lenzburg)	Car	-	360 m	0.26 min	- 985 m	3760 m
	Bus (current # lines)	4	251 m	0.34 min	- 695 m	
	Bus (new # lines)	6	467 m	0.47 min	- 785 m	
Muri (main demand direction to Rotkreuz)	Car	-	- 574 m	0.73 min	- 2115 m	3950 m
	Bus (current # lines)	4	- 681 m	0.92 min	-1830 m	
	Bus (new # lines)	6	- 574 m	0.94 min	- 1925 m	
Benzenschwil	Car	-	0 m	0 min	- 990 m	2940 m
	Bus (current # lines)	1	98 m	0.08 min	- 675 m	
Mühlau	Car	-	74 m	0.03 min	- 940 m	4300 m
	Bus (new # lines)	1	0 m	0 min	- 600 m	
Sins	Car	-	202 m	0.20 min	- 780 m	2550 m
	Bus (current # lines)	3	202 m	0.19 min	- 670 m	
	Bus (new # lines)	5	202 m	0.18 min	- 670 m	
Oberrüti	Car	-	104 m	0.01 min	- 1055 m	4160 m
	Bus (new # lines)	1	208 m	0.16 min	- 690 m	

Table 15: Results for corridor Winterthur - Wil

Town	Feeder system	line density [-]	Optimal location [m]	Travel time savings	Break-even location for cancellation	Distance to next down-stream station [m]
Hegi	Car	-	263 m	0.14 min	- 850 m	1400 m
	Bus (current # lines)	2	263 m	0.08 min	- 660 m	
	Bus (new # lines)	3	263 m	0.21 min	- 660 m	
Räterschen	Car	-	- 216 m	0.12 min	- 1650 m	2050 m
	Bus (new # lines)	1	- 216 m	0.15 min	- 955 m	
Schottikon	Car	-	- 99 m	0.02 min	- 1110 m	1330 m
	Bus (new # lines)	1	0 m	0 min	- 680 m	
Elgg	Car	-	107 m	0.02 min	- 1045 m	4380 m
	Bus (current # lines)	1	0 m	0 min	- 535 m	
	Bus (new # lines)	2	107 m	0.09 min	- 625 m	
Aadorf	Car	-	- 105 m	0.04 min	- 1475 m	3230 m
	Bus (current # lines)	1	0 m	0 min	- 1055 m	
	Bus (new # lines)	2	- 210 m	0.09 min	- 1055 m	
Guntershausen	Car	-	- 278 m	0.12 min	< - 2000 m	1940 m
	Bus (new # lines)	1	- 278 m	0.13 min	- 1550 m	
Eschlikon	Car	-	210 m	0.08 min	- 1025 m	3510 m
	Bus (current # lines)	1	210 m	0.08 min	- 735 m	
	Bus (new # lines)	2	210 m	0.11 min	- 735 m	
Sirnach	Car	-	- 246 m	0.21 min	- 1630 m	3620 m
	Bus (current # lines)	2	- 246 m	0.02 min	- 990 m	
	Bus (new # lines)	3	- 246 m	0.22 min	- 1195 m	
Wil	Car	-	203 m	0.07 min	- 1090 m	3210 m
	Bus (current # lines)	6	203 m	0.12 min	- 700 m	
	Bus (new # lines)	9	203 m	0.15 min	- 790 m	

Table 16: Results for corridor Glarus - Linthal

Town	Feeder system	line density [-]	Optimal location [m]	Travel time savings	Break-even location for cancellation	Distance to next down-stream station [m]
Ennenda	Car	-	0 m	0 min	< - 1000 m	880 m
	Bus (current # lines)	1	105 m	0.04 min	- 810 m	
Mitlödi	Car	-	- 261 m	0.21 min	- 1470 m	2780 m
	Bus (new # lines)	1	- 157 m	0.43 min	- 1160 m	
Schwanden	Car	-	546 m	0.56 min	- 1280 m	1550 m
	Bus (current # lines)	1	546 m	1.14 min	- 700 m	
	Bus (new # lines)	2	734 m	0.79 min	- 705 m	
Nidfurn	Car	-	0 m	0 min	- 1560 m	1960 m
	Bus (current # lines)	1	- 139 m	0.13 min	- 1080 m	
Haslen	Car	-	238 m	0.32 min	- 815 m	
	Bus (current # lines)	1	314 m	0.45 min	- 560 m	
Leuggelbach	Car	-	- 190 m	0.11 min	- 1080 m	1600 m
	Bus (current # lines)	1	- 285 m	0.02 min	- 900 m	
Luchsingen	Car	-	- 241 m	0.25 min	< - 1500 m	1310 m
	Bus (current # lines)	1	- 241 m	0.56 min	- 1080 m	
Hätzingen	Car	-	165 m	0.17 min	- 760 m	
	Bus (current # lines)	1	258 m	0.44 min	- 550 m	
Diesbach	Car	-	- 767 m	2.09 min	< -2500 m	2570 m
	Bus (current # lines)	1	- 854 m	2.26 min	- 2400 m	
Betschwanden	Car	-	- 216 m	0.23 min	- 1350 m	
	Bus (current # lines)	1	- 216 m	0.19 min	- 1050 m	
Rüti GL	Car	-	- 214 m	0.31 min	- 1345 m	1600 m
	Bus (current # lines)	1	- 319 m	0.02 min	- 1020 m	
Linthal	Car	-	133 m	0.01 min	- 1280 m	400 m
	Bus (current # lines)	1	133 m	0.12 min	- 865 m	

8.2.2 Preliminary conclusions

8.2.2.1 Corridor Lenzburg – Rotkreuz

Could stations be better placed?

Most stations are well placed. Shifts in the range of 200 m - 300 m are generally not worth to be investigated, as the train itself can have a length of almost 200 m.

The most notable exception is Hendschiken where the station is today very peripherally located. A repositioning could thus be beneficial. This would also open up opportunities for merger with the neighbouring station of Dottikon-Dintikon, where of all stations in the corridor the break-even for cancellation is closest to the current spacing and would be even closer with a relocation of Hendschiken's station. However, the station of Hendschiken is well placed with regard to the industrial zone where a number of jobs are located. The simulation's results are only based on resident population. In section 8.3, we will investigate this relocation and merger in detail.

For Muri, simulations of both demand directions yield the same qualitative result that a southwards relocation of the station would be beneficial. We will further analyse which pieces of land would be suitable therefore (see section 8.3).

Could stations be cancelled?

Spacing in-between the existing stations in the corridor Lenzburg – Rotkreuz is as of now comparably high with distances of 4 km or more. Moreover, the speed on the railway line is also comparably high, which is a consequence of the rather straight alignment. **Both factors do not favour the cancellation of existing stations.** The only case where a cancellation (or merger) could be useful is the one of Hendschiken und Dottikon-Dintikon. This merger would be favoured by the two facts that on the one hand the current station of Hendschiken is very peripheral and that on the other hand the towns of Dottikon and Dintikon have very distant break-even locations for cancellation (due to their town form perpendicular to the railway line). For further details see section 8.3.

8.2.2.2 Corridor Winterthur - Wil

Could stations be better placed?

The obtained shifts from the current to the optimal station location are all below 300 m. It is also interesting to note that for all towns the optimal locations of both feeder systems are either the same or very close. **The optimal location is thus very robust with respect to a potential change of feeder system.**

Could stations be cancelled?

For all towns except *Räterschen, Schottikon* and *Guntershausen*, the break-even location for cancellation is far away from the next downstream station. A cancellation would

thus be very inappropriate. For the three previously stated exceptions, the break-even location of the car-based feeder is either further downstream than the next station (i.e. cancellation clearly advisable) or fairly close. In the case of *Guntershausen*, even the break-even location of the bus-based feeder is very close to the next downstream station. It is the station that is most appropriate for cancellation. We will investigate this case more in detail in section 8.3.

8.2.2.3   Corridor Glarus - Linthal

Could stations be better placed?

Most shifts are below 300 m which makes a relocation rather useless. There are, however, two exceptions.

In *Schwanden*, the station is currently located at the northern end of the town. The results of the simulations suggest that it would be advisable to move it by 500 m to 700 m further south. The feasibility is however questionable, as the railway is passing in-between the houses such that not much space would be available to build a station and the corresponding interchange facilities to the feeders. Furthermore, the station is at the moment well placed for the connecting buses to/from Elm. With a relocation, this easy access would not be given anymore.

The station of *Diesbach-Betschwanden* is a joint station for two towns. Diesbach is the northern one of the two and Betschwanden the southern one. Currently the joint station is located at the southern end of Betschwanden, thus very peripheral with respect to Diesbach. Accordingly, the simulations yields that for Diesbach a shift of the station by around 700 m further north would be advisable. For Betschwanden the optimal shift would only be 200 m further north.

Both cases will be further investigated in section 8.3.

Could stations be cancelled?

The speed of the railway line in this corridor being lower than in the other corridors and the current spacing of the stations being smaller too, **this corridor is the most likely to contain suitable cases for cancellation**.

The station of *Ennenda* being very close to the neighbouring one of Glarus, the break-even location for cancellation of both feeder systems supports a cancellation.

Nidfurn-Haslen is again a joint station for the more northern town of Nidfurn and the more southern one of Haslen. Solely considering Nidfurn, the break-even location for cancellation of the car-based feeder would be close to the next downstream station Schwanden. A possible relocation of Schwanden would further speak in favour of cancellation. However, considering solely Haslen, the break-even for cancellation of both feeders is far away from the actual spacing.

The same considerations hold for *Luchsingen-Hätzingen* (Luchsingen being the more northern town and Hätzingen the more southern one). The simulation results of Luchsingen would support considering a cancellation while the ones for Hätzingen do not.

The same also holds for the joint station of *Diesbach-Betschwanden*.

In *Linthal*, the break-even location for cancellation is located further downstream than the next station: Linthal Braunwaldbahn (the latter was not considered for a separate simulation, as it does not serve a residential area around it, but the lower station of the cablecar going up to Braunwald). From this perspective, it would be advisable for Linthal to cancel the final station with trains terminating at Linthal Braunwaldbahn instead. This case will also be further investigated in section 8.3

8.3   Detailed investigation of selected towns

Besides the towns where a relocation or cancellation is interesting to investigate (see above), we will also have a look at the most used stations in the respective corridors. They are the ones where the need for land in case of a car-based feeder is the largest. Given the high number of passengers, potential limitations of the available road capacity for the feeder service by other traffic participants have the largest effects, as it would lead to not all passengers being able to reach the station within the expected time frame.

In the remaining part of this chapter we will thus have a detailed look at the following cases:

- **Corridor Lenzburg – Rotkreuz**

  - Merging the stations of Hendschiken and Dottikon-Dintikon

  - Capacity check for the station of Wohlen

  - Relocation of the station of Muri, including capacity check

- **Corridor Winterthur – Wil**

  - Cancellation of the station of Guntershausen, including capacity check for the nearest downstream station at Aadorf

  - Capacity check for the station of Wil

- **Corridor Glarus - Linthal**

  - Cancellation of the station of Ennenda including capacity check for the nearest downstream station at Glarus

  - Relocation of the station of Schwanden

  - Relocation of the station of Diesbach-Betschwanden

  - Cancellation of the station of Linthal including capacity check for the nearest downstream station at Linthal Braunwaldbahn

8.3.1 Corridor Lenzburg – Rotkreuz

As stated previously, the demand is assumed to split up on the two directions inversely proportionally to the respective travel times. For the towns we will subsequently consider, the peak frequencies given in Table 13 will thus split up as stated in Table 17.

Regarding the repartition of demand on the single trains, we will only consider the trains being part of the basic all-day offer. Single, peak-hour or weekend trains (partly with a different route, e.g. running directly to Zurich) are neglected in the present study. The subsequent analysis could easily be repeated with more precise data containing the exact number of alighting or boarding passengers per train. Unfortunately, this was not possible for the present project as the corresponding data was not available.

Table 17: Split-up of passengers in corridor Lenzburg – Rotkreuz

Station	Travel time [min] to…		Total peak passenger frequency per direction	Peak frequency to/from to …	
	Lenzburg	Rotkreuz		Lenzburg	Rotkreuz
Hendschiken	3	30	50	45	5
Dottikon-Dintikon	6	27	176	144	32
Wohlen	9	24	682	496	186
Muri	16	16	286	143	143

8.3.1.1 Merging the stations of Hendschiken and Dottikon-Dintikon

Identification of suitable locations
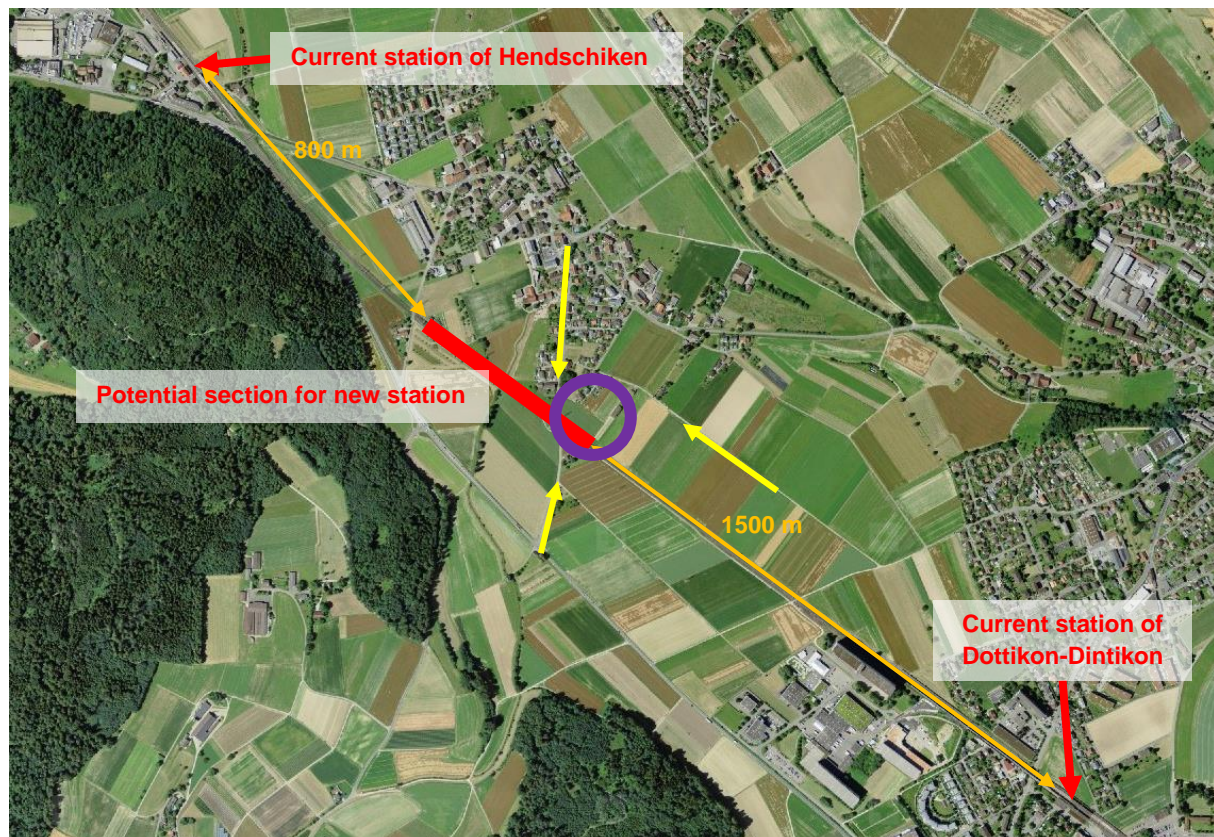
Figure 44: Aerial picture of Hendschiken and Dottikon-Dintikon
(Bundesamt für Landestopographie (swisstopo), 2018)

The current spacing between the two existing stations is 2720 m. According to Table 14, the optimal location of the new station with respect to Hendschiken would be around 800 m further south of the current one (thus hypothetically decreasing the spacing to 1920 m). With respect to Dottikon, the break-even location for cancellation is at around 1700 m north of the current station of Dottikon-Dintikon, while it is at around 1500 m north with respect to Dintikon.

Figure 44 shows an aerial picture of the area under consideration. It also translates the afore-mentioned boundary values into concrete locations. The potential section for the new merged station (marked in red) is located at the southern end of the town of Hendschiken. If we additionally consider the intention to make the new station as easily accessible via the existing road network as possible (i.e. without the need to construct much new road infrastructure), the area shown by the violet circle in Figure 44 is best suited to receive the station and its drop-off / boarding as well as storage facilities.

Capacity calculation with car-based feeder system

Three roads marked by the yellow arrows in Figure 44 lead to the new merged railway station, each connecting one of the three towns. With that, the **area for the drop-off / boarding area is roughly 4000 m²**. Remember that a full drop-off area is required per access road, as the highest possible peak flow is determinant for the design flow and not the expected total number of vehicles!
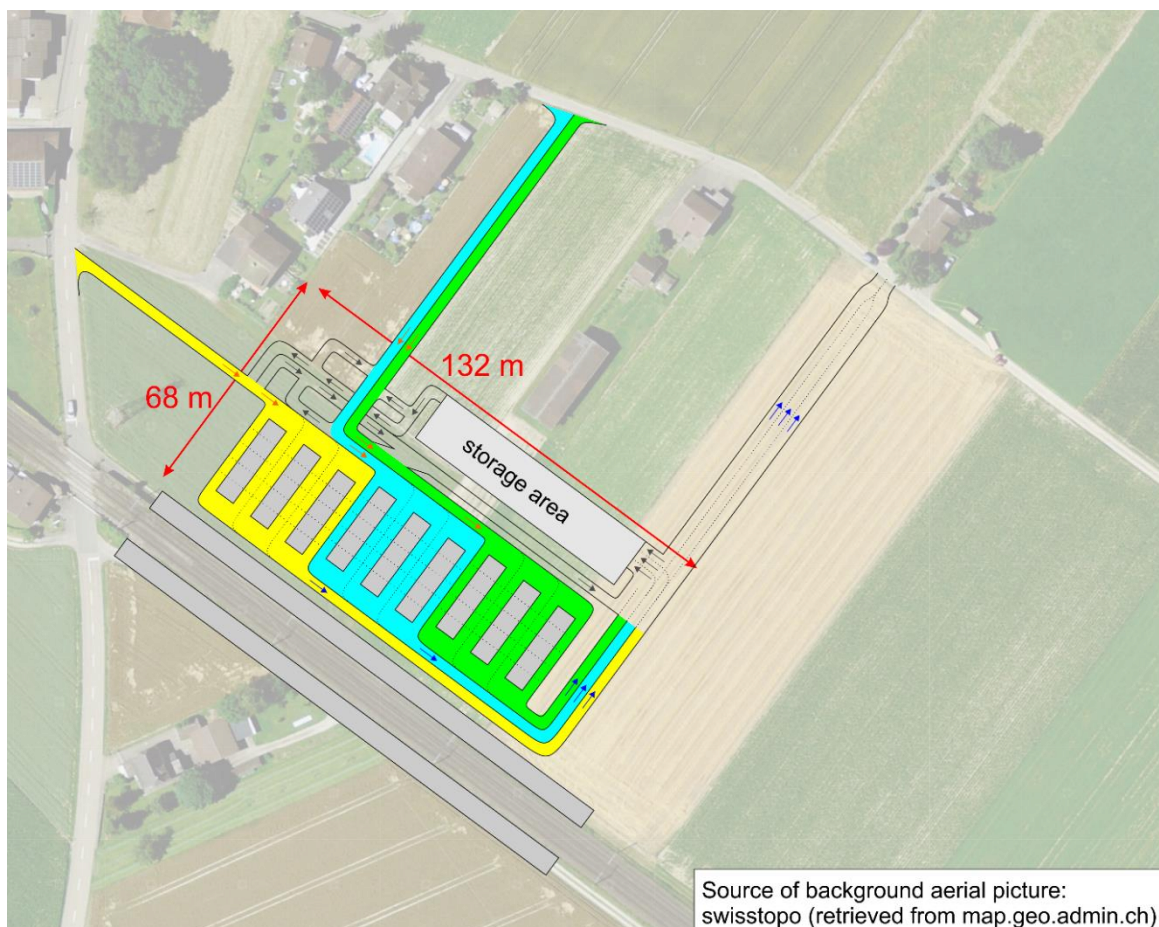
Figure 45: Possible layout of merged station Hendschiken-Dottikon-Dintikon

The maximum number of passengers able to arrive is thus 3 * 347 passengers = 1041 passengers. With a peak-hour train frequency of two trains per direction, we obtain based on Table 17 that the design-load train brings (45+144) / 2 = 95 passengers (which is much less than the absolute maximum capacity of 1041 passengers). With the assumed occupancy rate of 1,6 passengers per car (see section 4.2), we obtain 60 vehicles waiting for use, such that we need **a storage area of at least 750 m^2**.

Figure 45 shows a possible layout of the interchange facilities. Three drop-off areas, one for each access road are shown in yellow, blue and green respectively. Including all access and exit lanes, the total area grows to almost 9000 m^2, which is almost the double (189%) of what is needed for the drop-off / boarding and storage areas alone. The surface of the access and exit lanes shall thus not be underestimated.

8.3.1.2   Capacity check for the station of Wohlen

Wohlen is the busiest station on the corridor Lenzburg – Rotkreuz. It features the additional difficulty that the trains to/from Lenzburg and Rotkreuz both arrive and depart close to each other (only 3 to 4 minutes difference, see netgraph in Figure 46). Thus the streams of arriving or departing passengers of both directions do partly superpose. We will subsequently make the conservative assumption that they do fully superpose, such that passengers' arrival or departure with the feeder system is happening during the same 5 minutes.
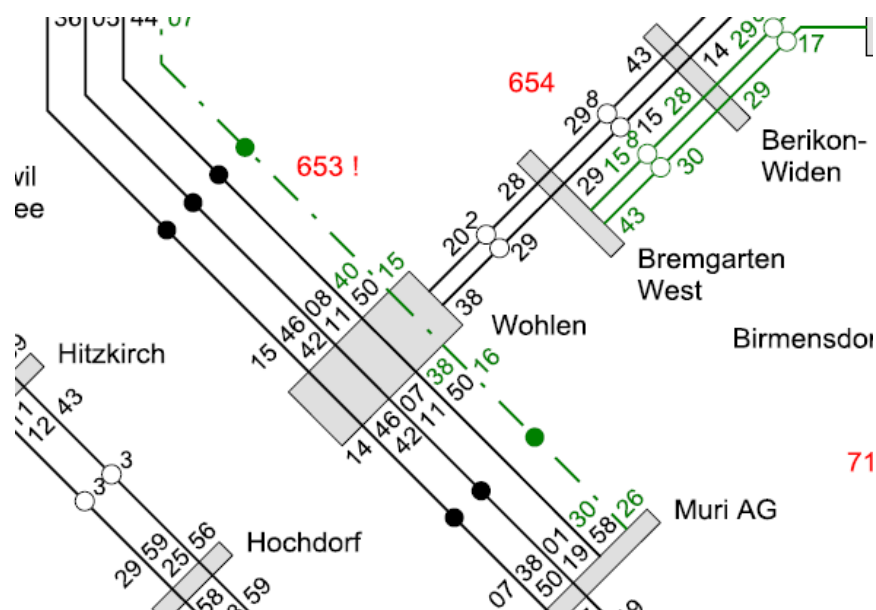
Figure 46: Extract of „Netzgrafik Schweiz" (SMA und Partner AG, 2017)

Capacity calculation for car-based feeder system

The design load of passengers arriving in 5 minutes is thus 682 / 2 = **341 passengers**. This is very close to the absolute maximum of 347 passenger being able to arrive over one single access road. Hence a second access road is certainly necessary in order to assure the appropriate operational stability and to cover the inevitable peaks exceeding the standard temporal

distribution of demand. With two access roads, the **area required for drop-off and boarding** is almost **2700 m^2**. The size of the storage area is as follows:

$$341 \text{ passengers} / 1,6 \text{ passengers/car} * 12,5 \text{ m}^2\text{/car} = 2664 \text{ m}^2$$

Drawing from the previously analysed case of Hendschiken-Dottikon-Dintikon, where the total area was 89% larger than drop-off/boarding and storage facilities, we can expect the total area of the station in Wohlen to be around 10'000 m^2.

Identification of suitable locations

Figure 47: Aerial picture of Wohlen
(Bundesamt für Landestopographie (swisstopo), 2018)

Figure 47 shows an aerial picture of the area around the current station of Wohlen. Although the red-marked area in the lower part (next to the current station) has a surface of slightly more than 10'000 m^2, its long-stretched form is very unsuitable to place the interchange facility – with two access roads – in a compact way. The other red-marked area in the upper part of Figure 47 is significantly bigger (> 25'000 m^2) and has a form that makes it easier to fit the interchange facility. It does, however, not correspond to the optimal location of the station. The alternative to both areas is an interchange facility using the second level in space, i.e. either an underground drop-off/boarding facility, or one located above the railway tracks on a bridge.

8.3.1.3   Relocation of the station of Muri

Identification of suitable locations

From the results in Table 14 we conclude that the station should ideally be moved roughly 500 m southwards so as to be ideally located for passengers arriving or departing to/from both directions. Figure 48 shows an aerial picture of the area of interest. A shift of around 500 m yields a location on a former industrial piece of land (red shape left of the railway tracks), which – according to Figure 48 – has not yet been reconstructed. Given the high values of land property in general, one must, however, expect that this stretch of land will be rebuilt in the coming years. In the immediate vicinity, there is another piece of land on the other side of the railway tracks (other red shape on the right side) which could be potentially suitable to establish the railway station together with the feeder facilities.

Figure 48: Aerial picture of Muri
(Bundesamt für Landestopographie (swisstopo), 2018)

Capacity calculation for car-based feeder system

In Muri, the arrivals or departures of the trains from/to both directions do not superpose each other as they do in Wohlen. The capacity calculation can thus be done with the peak load of a train from a single direction, which according to Table 17 is 143 / 2 passengers = 72 passengers. This load is easily manageable on a single drop-off area. However, a road access from two directions, as the area shown in Figure 48 would have (one road from the north, one from the south), requires a doubling of the drop-off area. The **corresponding size of land for drop-**

off / boarding is thus almost 2700 m². The number of vehicles to be stored in case of shared cars is 72 / 1,6 = 45 cars which yields a **minimum size of the storage facility of almost 600 m²**. All in all, the total size of the connection facility with drop-off / boarding area, storage as well as access and exit lanes can be expect to be around 6000 m². Of the two areas shown in Figure 48, the one on the left side of the tracks (former industrial area) could easily fit this size of feeder facility, while the other one on the right side of the railway tracks cannot: it is only 5500 m² large.

8.3.2 Corridor Winterthur – Wil

8.3.2.1   Cancellation of the station of Guntershausen with capacity check for Aadorf

The station of Guntershausen is the one on the corridor Winterthur – Wil that is most suitable for cancellation. There are two main reasons for this result. On the one hand, the town has a long stretched form along the main road which yields to comparably high average speeds on the road network (see Table 13). On the other hand, the distance to the next downstream station in Aadorf is the one of the smallest on the entire corridor (< 2000 m). The combination of these two mutually reinforcing factors leads to the described result.

Figure 49: Aerial picture of Guntershausen
(Bundesamt für Landestopographie (swisstopo), 2018)

Capacity calculation for Aadorf for car-based feeder system

When cancelling the station of Guntershausen, we assume that all its passengers will use a feeder system to reach the neighbouring station of Aadorf where they will add up to the original demand of the latter. Moreover, Aadorf is the most used station on the entire corridor (with the exception of the regional centre Wil). Hence the new design load on a single train departing Aadorf is:

$$(220 + 46) / 2 = 133 \text{ passengers.}$$

Basically, this load is well manageable by a single drop-off area which can receive up to 347 passengers per train. However, we assume that at least two access roads will yield to the station (one from the northwest and one from the southeast); thus we will need to foresee space of roughly **2700 m² for the drop-off and boarding facility**. The **storage area** will need to accommodate 133 / 1,6 cars, which yields an area of **1000 m²**. Including all access and exit ways, we expect the total area to require roughly 7000 m².
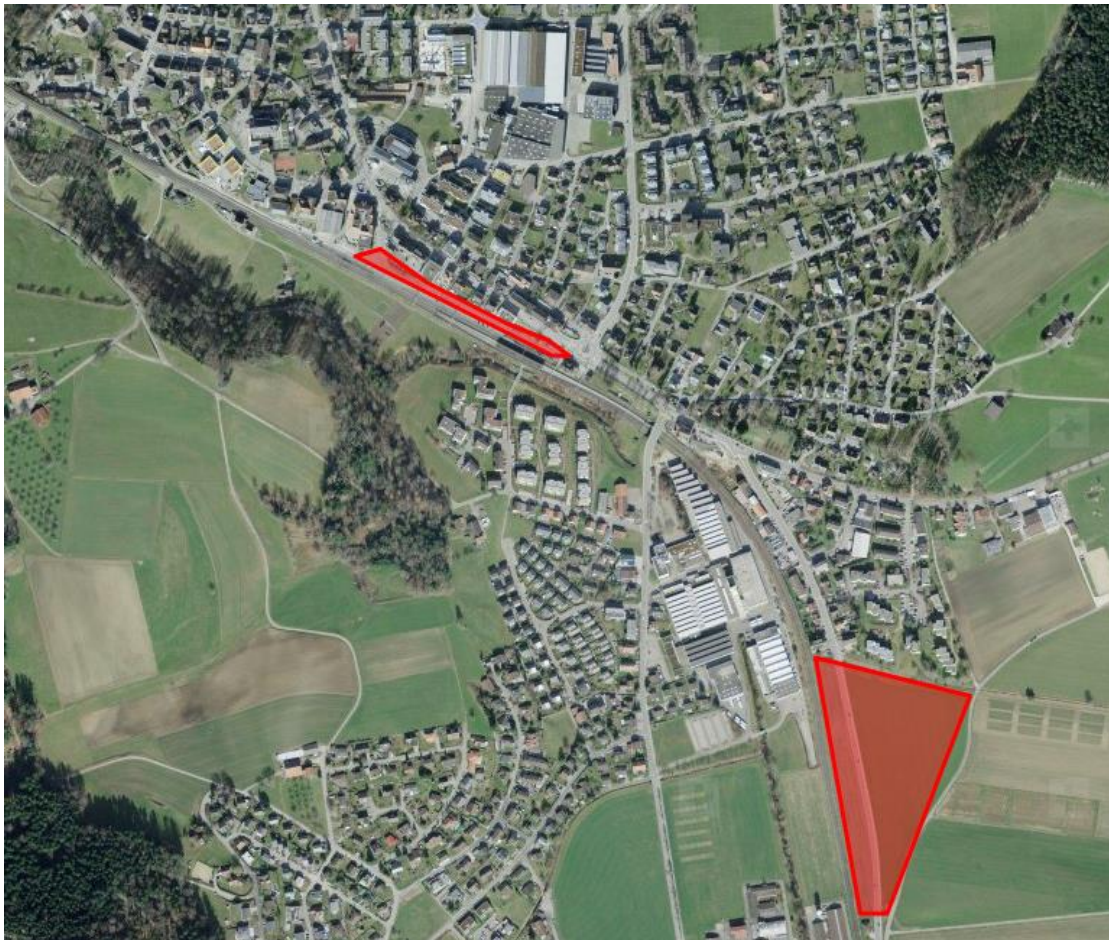
Figure 50: Aerial picture of Aadorf
(Bundesamt für Landestopographie (swisstopo), 2018)

Identification of suitable locations

In the immediate vicinity of the current station of Aadorf, there is no sufficiently large area able to accommodate the entire feeder facility. The area currently used for P+R and bus stops (red shape in the top half of Figure 50) is only 4500 m² large. On the one hand, this is way below the expected minimum size. On the other hand, the long-stretched shape makes it difficult to arrange all facilities in a compact way. On the other side of the railway tracks, there is unbuilt land available, but it lacks an adequate access road.

Looking for an alternative piece of land along the railway line, the area at the south-eastern end of Aadorf seems the most suitable (red shape in lower half of Figure 50). It is also well accessible from Guntershausen, as it located along the main road connecting the two towns. It is sufficiently large to accommodate the feeder facility without any problems.

Suitability of a bus-based feeder system

The connection between Guntershausen and the (current or relocated) station in Aadorf can also be offered by an autonomous bus line. The town form of Guntershausen, long-stretched along the main road, is very suitable in this respect, so that time-losses compared to a car-based feeder system are not too big.
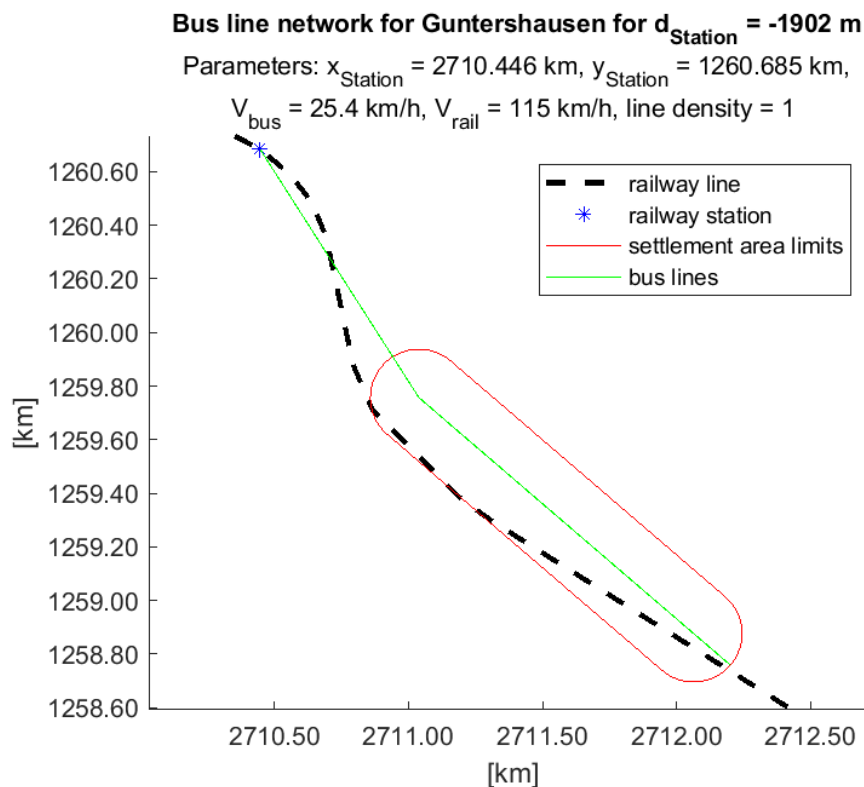
Figure 51: Generic bus network of Guntershausen (departing the current station of Aadorf)

Figure 51 shows the generic bus network of Guntershausen consolidated by the simulation environment. It departs from the current station of Aadorf. Figure 52 shows the corresponding mean travel time savings as a function of the station location. It is true that the break-even for

cancellation (located at -1550 m, as stated in Table 15) is not as far downstream as it needs to be in order to provide full travel time equality.

However, **one shall note that the travel times for the reference location (i.e. the current station location) also assume the existence of a feeder service (with autonomous buses), i.e. they do not correspond to the status quo!** If we want to compare potential future travel times with a bus-based feeder service departing from Aadorf to the current travel times (i.e. no feeder existing in Guntershausen), the travel time loss of the feeder service option is smaller than predicted through Figure 52. In order to draw a comparison with the status quo, one needs to shift the travel time savings function in Figure 52 further up, thus obtaining a break-even location for cancellation that is further left.

Mean Travel Time Savings for Guntershausen as function of d$_{Station}$
Parameters: V$_{bus}$ = 25.4 km/h, V$_{rail}$ = 115 km/h, line density = 1,
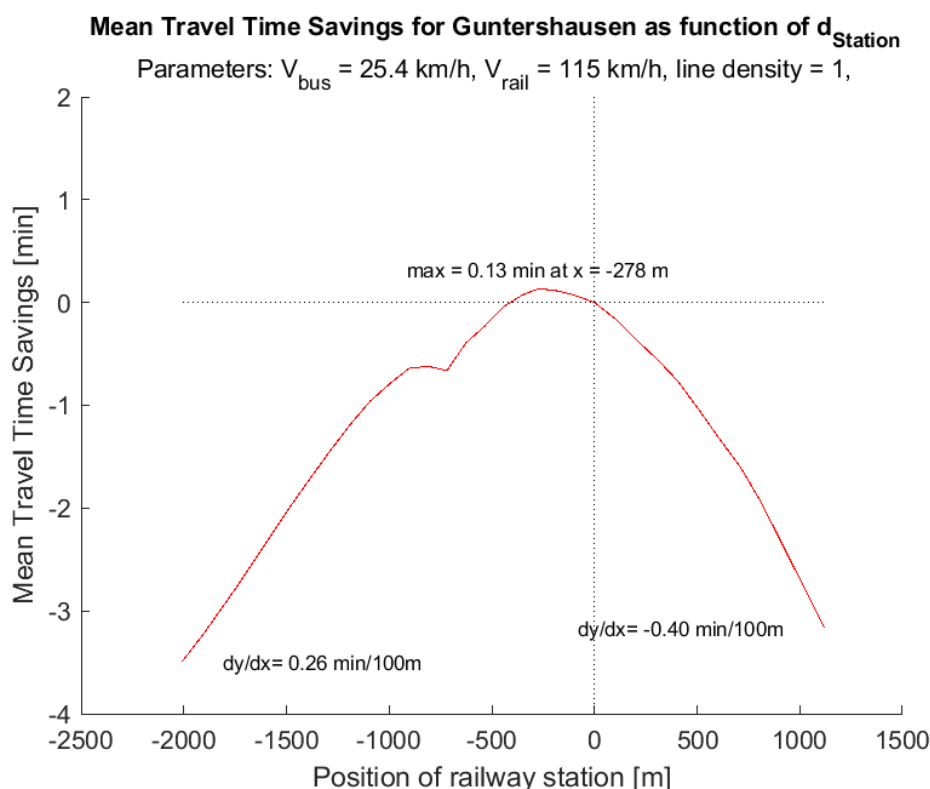
Figure 52: Bus-feeder Mean Travel Time Savings for Guntershausen as a function of the station location

8.3.2.2   Capacity check for the station of Wil

Capacity calculation for car-based feeder system

A meaningful capacity check for the station of Wil is hardly possible, as we do not know the share of passengers transferring between trains among the peak frequency of 2464 passengers/h/direction. In the current statistics, a passenger transferring between two trains is counted twice, while he/she does not require a road-based feeder service. Train-sharp data in this respect would greatly improve the quality of the result. Unfortunately, it was not available form this project.

If we assume that 50% of all passengers are transferring, and that the other 50% of passengers using the road-based feeder arriving at/departing from the station of Wil do equally split up on the two directions (Winterthur – Zurich as well as St. Gallen with two trains per hour each), we obtain a design load of 308 passengers per single train. In terms of traffic volume, this is very comparable to the case of Wohlen where we estimated a total size of feeder facility of roughly 10'000 m^2. Similarly to Wohlen, recurring to one single access road would theoretically be sufficient to carry the load, but highly unstable. Two access roads are thus assumed for the case of Wil, too.

Identification of suitable locations

Figure 53 shows an aerial picture of the area around the station of Wil. The red shape, which includes the current square in front of the station where buses right now depart and arrive (minor part) as well as installations currently occupied by the Frauenfeld – Wil narrow gauge railway (major part), has an area of roughly 14'000 m^2. The establishment of a sufficiently large drop-off and boarding facility at the station of Wil is only possible at the expense of usages currently established on these lands. The alternative is again an underground or on-bridge feeder facility, which is possible too.

Figure 53: Aerial picture of Wil
(Bundesamt für Landestopographie (swisstopo), 2018)

8.3.3 Corridor Glarus – Linthal

8.3.3.1 Cancellation of the station of Ennenda with capacity check for Glarus

The cancellation of the station of Ennenda is potentially meaningful because of the very small distance to the next downstream station in Glarus on the one hand and the low speed on the railway line on the other hand.

Identification of suitable locations

Figure 54 shows an aerial picture of the town of Glarus with the immediate vicinity of the railway station. The only area potentially suitable for a feeder facility is the one of the park opposite to the railway station (red shape in Figure 54, size around 6000 m^2). One may doubt that it will be politically feasible to sacrifice the park in the town centre for a feeder interchange facility. The alternative is obviously as always the construction of an underground or on-bridge facility.

Capacity calculation for Glarus for car-based feeder system

The total peak design load per train for the station at Glarus is (352 + 68) / 2 = 210 passengers. This load is easily manageable by a single drop-off area. However, as we can see through the yellow arrows in Figure 54, this interchange facility is accessible from three sides. We would thus need three drop-off area to be sure to be able to cover the maximum inflow without spill-backs to the road network. A surface of roughly **4000 m^2** is thus required **for the drop-off areas alone**.

Figure 54: Aerial picture of Glarus (Bundesamt für Landestopographie (swisstopo), 2018)

The storage area needs to be able to accommodate at least 210 / 1,6 = 131 car, which corresponds to roughly 1600 m². With all the access and exit ways, the total size of the interchange facility will be between 10'000 m² and 11'000 m² which exceeds the available size of the only theoretically available area.

Suitability of a bus-based feeder system

The establishment of a car-based feeder system in Glarus is thus not easily possible under the assumed capacity requirements. In return, an autonomous bus-service is very suitable to connect the town of Ennenda in case of cancellation of its own station. The town of Ennenda is comparably compact which makes it easy to cover the entire town with a bus line departing from the current station at Glarus (see Figure 55). Additionally the distance to the station of Glarus is small and the latter is easily accessible from road-wise.
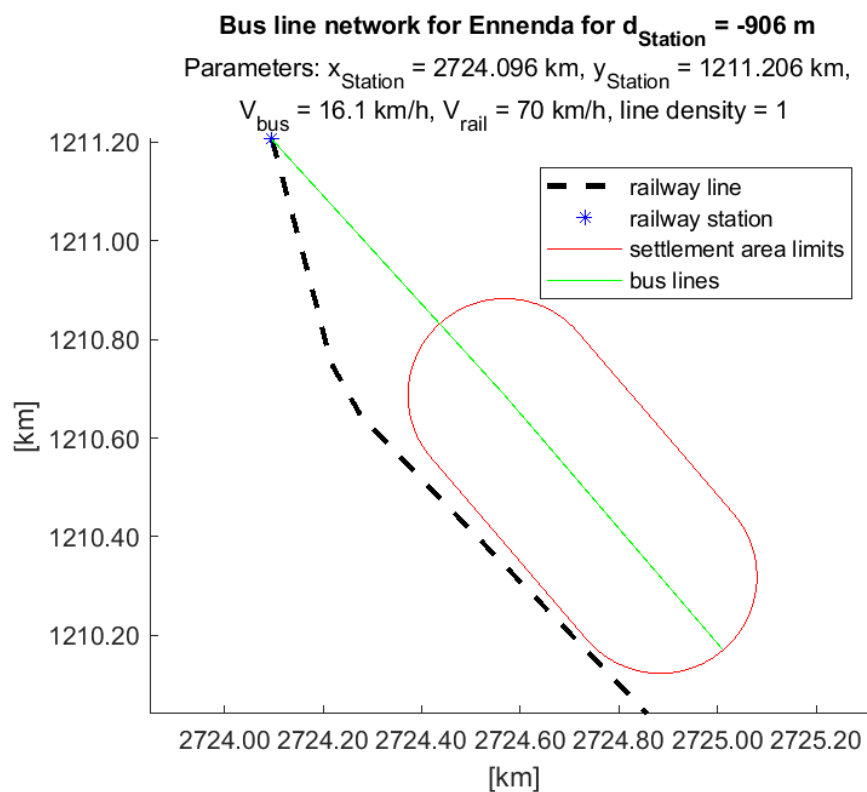
Figure 55: Generic bus network of Ennenda (departing the current station of Glarus)

Figure 56 shows the mean travel time savings function of Ennenda as a function of the station location. We notice that even for locations close the next downstream station of Glarus (located at -880 m), the travel time savings are above or not far below - 2 min, as the break-even location for cancellation of -810 m (see Table 16) shows.

Again, the same remark as made above for the case of Guntershausen applies: the travel time savings function assumes also for the reference location (i.e. current station location) the existence of a feeder service. Today there is a bus line serving Ennenda, but it is not coordinated

schedule-wise with the trains at its own station. *De facto*, there is thus no feeder service currently existing for the town of Ennenda.
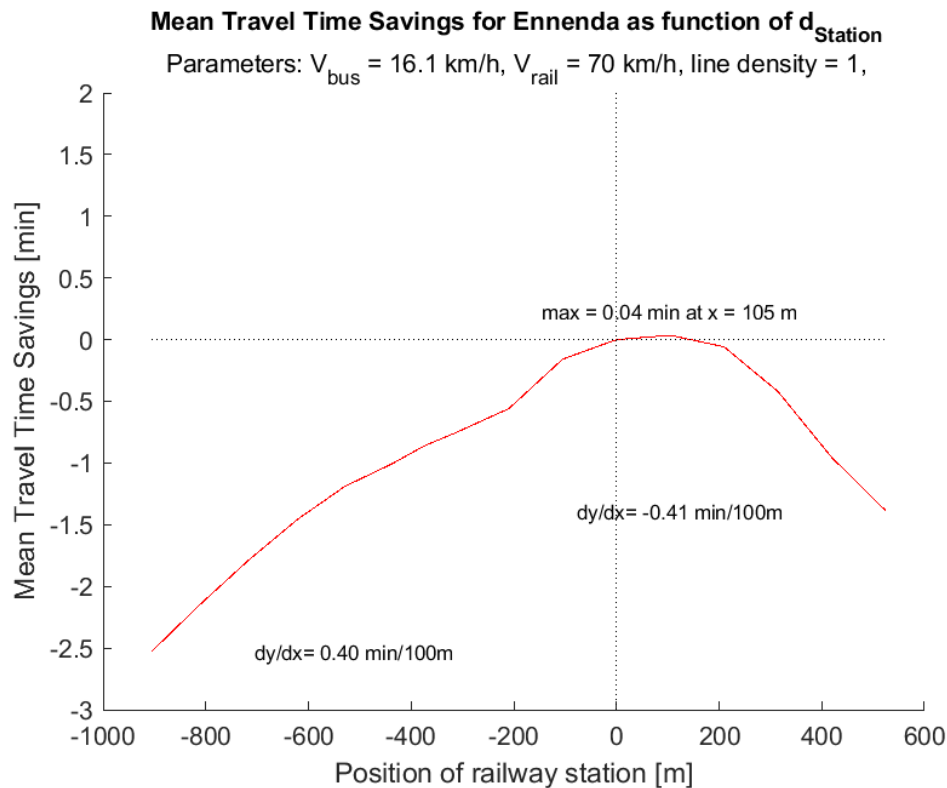
Figure 56: Bus-feeder Mean Travel Time Savings for Ennenda as a function of the station location

8.3.3.2   Relocation of the station of Schwanden

Identification of suitable locations

According to Table 16, the station of Schwanden would need to be moved 500 – 700 m (train line distance, not aerial distance) further southwards in order to provide optimal travel times for the town of Schwanden itself. Figure 57 shows an aerial picture of the town of Schwanden. The potentially ideal line section for the establishment of the station would be the one marked in orange in Figure 57. We see that the railway passes through a densely built environment, where space of sufficient size to establish a feeder interchange facility is not available. The only free space along the orange-marked section is the car park marked in red. However, with a size of less than 2000 m^2 it is largely insufficient to accommodate the entire drop-off / boarding and storage facilities. A detailed capacity check is thus not even needed. This stretch of land has some other strong disadvantages:

- All cars accessing the feeder facility would need to cross the railway line first, which is critical before train departure when the closing road-cross could lead to breaks of connections. An underpass would obviously be an option but the space for ramps is very limited due to existing buildings and the neighbouring river.

- Traffic from Sernftal (road marked in yellow in Figure 57) would need to pass through the town centre.

A relocation of the station in Schwanden is thus not possible. Even around the current station, the available space is insufficient to establish a full interchange facility for an autonomous car-based feeder system. Bundling of demand on a few, but larger vehicles is thus absolutely necessary.

Figure 57: Aerial picture of Schwanden (Bundesamt für Landestopographie (swisstopo), 2018)

Considering that (a) relocation of the Schwanden station cannot happen, and (b) a car-based feeder system is not possible, the cancellation of the next upstream station of Nidfurn-Haslen is not adequate. From the perspective of the town of Nidfurn alone, cancellation would have been meaningful with a relocated station of Schwanden and a car-based feeder system (current spacing 1960 m, with hypothetical relocation of Schwanden reduced to 1400 m; break-even for cancellation of car-based feeder at -1560 m with respect to the current station Nidfurn-Haslen). However, as a bus-based feeder system is the only option, the break-even for cancellation is too far upstream such that a cancellation of Nidfurn-Haslen would make sense (-1080 m for Nidfurn, -560 m for Haslen, while spacing kept at 1960 m).

8.3.3.3   Relocation of the station of Diesbach-Betschwanden

This is a very particular case to be investigated. Figure 58 shows the aerial picture of the two towns Diesbach (in the upper half of the aerial picture) and Betschwanden (in the lower half of the aerial picture). They are separated by a small river. The current station (shown by the red marker in Figure 58) is located at the southern end of Betschwanden. With respect to Diesbach, the station is thus located very far upstream which is generally disadvantageous as it involves backward connections.

Figure 58: Aerial picture of Diesbach-Betschwanden (Bundesamt für Landestopographie (swisstopo), 2018)

In terms of optimal locations and break-even location for cancellation, the results in Table 16 are as follows:

- *Diesbach:* optimal location at -800 m, break-even location for cancellation at -2400 m and ca. -3000 m for bus- and car-based feeder respectively

- *Betschwanden:* optimal location at -200 m, break-even location for cancellation at -1050 m and -1350 m for bus- and car-based feeder respectively

- The spacing to next station downstream is 2570 m

In the light of these results, a cancellation would make sense from the point of view of Diesbach, while it does not from the point of view of Betschwanden. While for Diesbach, the optimal location would justify a relocation, it would not from the perspective of Betschwanden.

Two options for action can thus be identified based on these numbers:

1. The current station of Diesbach-Betschwanden is kept as a joint station and moved 500 – 600 m further downstream. While it leads to a significant improvement for Diesbach (see markings labelled "Option 1" in Figure 59), it does at least not worsen the situation for Betschwanden to a notable extent (see corresponding markings in Figure 60).
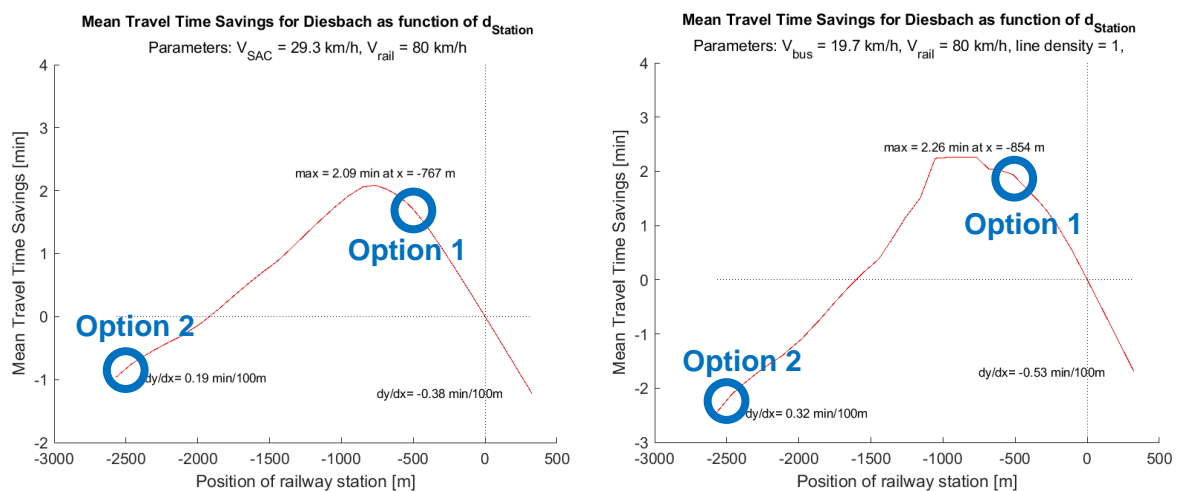
Figure 59: Mean Travel Times Savings function for car- and bus-based feeder for Diesbach
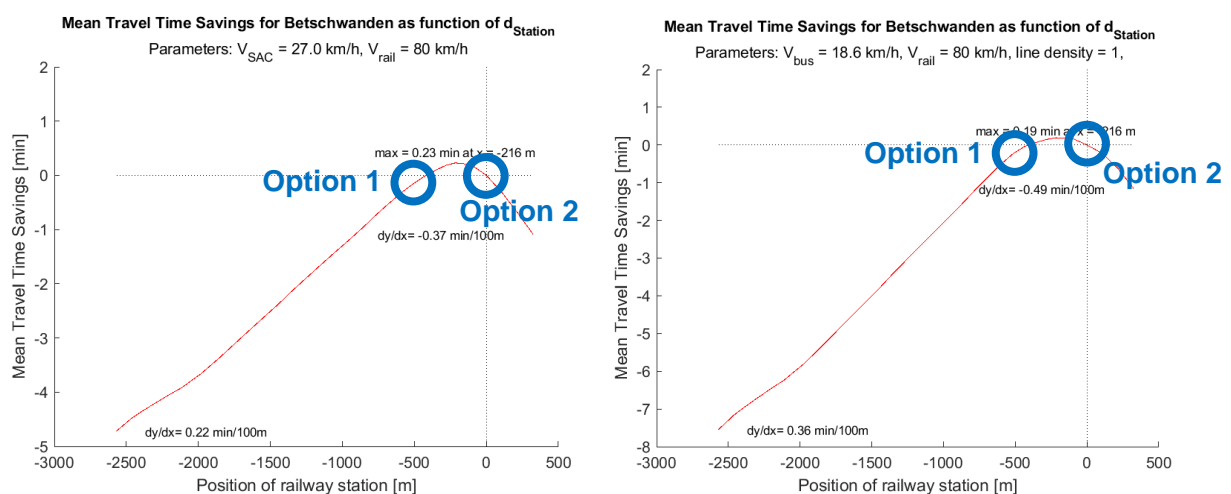
Figure 60: Mean Travel Times Savings function for car- and bus-based feeder for Betschwanden

2. The current station location is kept, but continues to only serve Betschwanden. For the latter there no changes in terms of travel time (see marking labelled "Option 2" in Figure 60). Diesbach will be served by a feeder departing from the station of Luchsingen-Hätzingen. In the case of a car-based feeder, this station is far upstream of the break-even for cancellation such that the net travel time gain is positive. For a bus-based feeder, the station of Luchsingen-Hätzingen is slightly downstream of the break-even for cancellation such that the net travel time gain is negative (i.e. a loss; see also the corresponding markings in Figure 59).

Once again, like in the cases of Guntershausen and Ennenda, one shall however note that the travel time savings function of the bus-based feeder case compares to a reference location with a feeder service and not to the status quo without an existing feeder service.

Which option to choose depends on how quick autonomous feeder systems are deemed to become reality. Independently of the available feeder systems, option 1 is a net improvement compared to the status quo for Diesbach and a similarly good situation as today for Betschwanden. But it requires an investment to move the station. Option 2 does not need an investment, but requires an autonomous feeder service to be available in order to realize travel time gains.

8.3.3.4   Cancellation of the station of Linthal

The station of Linthal is located only 400 m away from the next downstream station Linthal Braunwaldbahn. This very small distance combined with the low speed of the train on this section (only 60 km/h) is the most favourable setting for the cancellation of a station. Figure 61 shows the aerial picture of Linthal. The two red markers indicate the locations of the two stations "Linthal" (marker in the lower half) and "Linthal Braunwaldbahn" (marker in the upper half). The distance between both stations is only 400 m. In the picture we can see that both stations are not really centrally located, even if the one of Linthal is closer to the town located further south as well as to the east.

Under the usual assumption that in both cases passengers use a feeder service to gain the station as well as to get back to their homes again, it becomes evident that it is travel-time-wise more efficient to start the feeder service trip at the most downstream station.

Identification of suitable locations

Immediately next to the station of Linthal Braunwaldbahn there is an unbuilt area (red shape in Figure 61) which could be used to establish the feeder interchange facility. It has a surface of over 9000 m^2 which is sufficient for the establishment of the drop-off / boarding as well as vehicle storage facilities.

Capacity check

The very low passenger volume present in Linthal (39 passengers in the peak hour, i.e. 39 / 1,6 = 24 cars) could easily be accommodated by a single drop-off area. If the surrounding road network is adapted such that only one access road exists (e.g. through one way streets), the total area necessary for the drop-off / boarding facility would be 1300 m^2. The area required

for the storage of vehicles would be only 300 m². The total area including access and exit ways is roughly 3000 m² which can easily fit on the previously mentioned stretch of land.
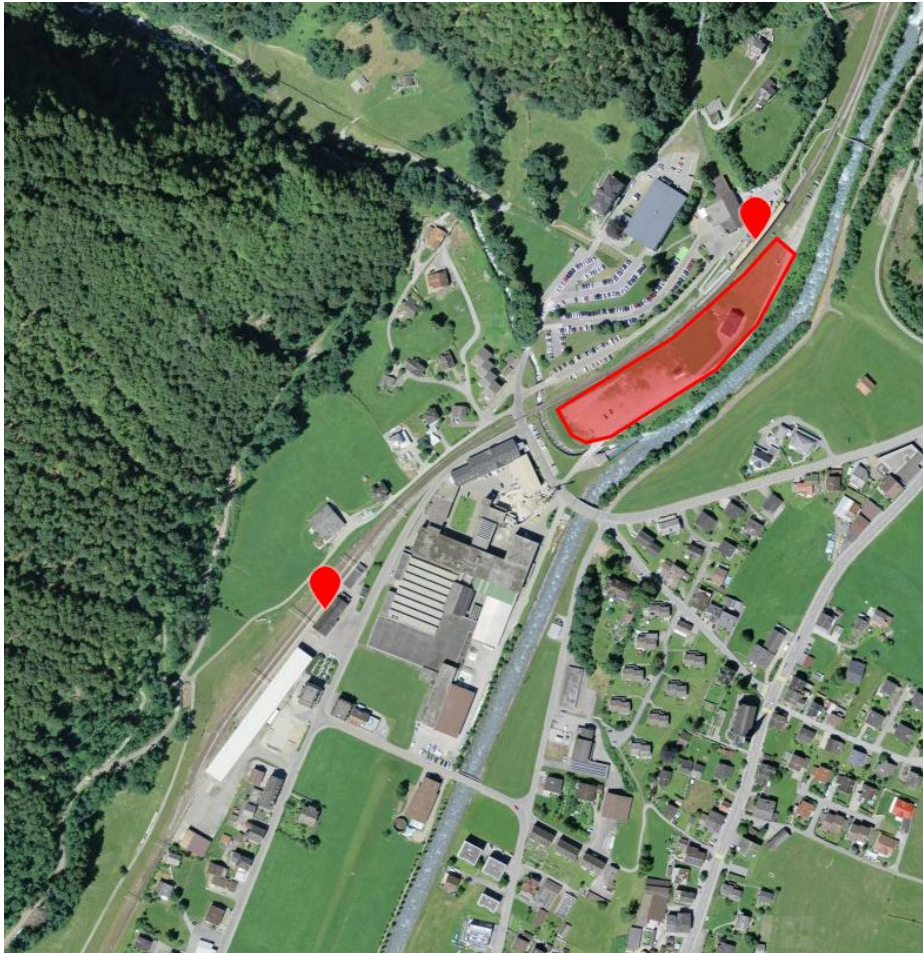
Figure 61: Aerial picture of Linthal (Bundesamt für Landestopographie (swisstopo), 2018)

9   Conclusions

In this chapter we will provide concluding answers to the four subsidiary research questions, before addressing the overall question of the present project.

9.1   Answering the subsidiary research questions

1. **Which are the micro-level space requirements for a railway station to work as an interchange between a feeder service and railway in terms of road accessibility, space for drop-off and boarding, space for parking, etc.?**

   For a car-based feeder system, the size of the drop-off area does not depend on the absolute number of passengers arriving at the station before the departure of the design load train, but on the maximum peak inflow being able to reach the station from the road network (see Figure 10 and Figure 11). Without further information or the presence of limiting mechanisms, this flow must be assumed equal to the number of access roads multiplied by the saturation flow of autonomous cars ($\mu \cong 2'600\ veh/h$) on each of them. The total space need furthermore depends on the size of the storage area which does depend on the absolute number of vehicles arriving and not on the maximum flow. Together with the access and exit ways, space of several thousand square meters is required for an interchange facility designed to receive autonomous cars as feeders.

   In return, the bus-based feeder system does not feature the above problems, as it is a planned system where the number of vehicles is first of all much lower, and secondly precisely known in advance so that drop-off areas can be tailored more efficiently to the effective use.

2. **What are the achievable benefits by using autonomous shared cars and autonomous buses as feeder services compared to the status quo?**

   With regard to a car-based feeder, the passage from traditional to autonomous cars does not yield any gains in terms of travel time savings. Speeds of autonomous vehicles can be assumed to be roughly the same as of now.

   With regard to a bus-based feeder, an increase of the line density on the bus network, e.g. thanks to automation, does not lead to significant travel time savings either (travel time savings in the order of +/- 1 min). The travel distance on the vehicle cannot be shortened much. Only the access/egress times are shortened. The latter, however, allow for a significant, although under-proportional, increase in ridership.

   Travel times via a car-based feeder system are significantly lower than those of a bus-based feeder, because of shorter ride distance, higher speed and non-existent access/egress times. In absolute numbers, the difference in roughly 5 minutes of travel time for station locations close to the town centre. When only looking at the short travel distance between station and final origin/destination, these 5 minutes are a significant difference. However, if one considers the total door-to-door travel time, the relative share of the 5 min difference decreases a lot.

3. What are the benefits in terms of travel time, if railway stations are relocated? Which implications would such a relocation have on urban planning? Is a relocation advisable from the urban planning perspective?

The benefits in terms of travel times of relocating stations are generally small, if the station is currently centrally located. The optimal location depends on several factors of which the respective speeds of rail and feeder have a particularly high influence. It has been analysed how the optimal station differs between car- and bus-based feeder systems. One can say that the optimal station locations on railway lines with comparably low speeds, passing outside the towns they serve are the least robust when it comes to changes of feeder systems. In regard to the form of the town, the perpendicular towns stretching far away from the railway line are the least robust in terms of optimal station location. As both the optimal location and the realizable travel time savings are scaled with the size of the towns, large towns feature the highest travel time savings and are thus the most valuable for potential relocations.

4. What are the benefits in terms of travel time, if the station density along a railway line decreases (i.e. one or more stops can be omitted)? Which implications does it have on urban planning?

First we analysed the implications of **adding or cancelling a second station within the same long-stretched town parallel to the railway line**. Generally speaking one can say that the additional travel time savings through the second station are relatively modest for both feeders, while being slightly larger for the bus-based feeder. If one expects autonomous cars to take over the role as feeders, building new additional stations is not meaningful as the latter might not reach (time-wise) the economic pay-back of the investment linked to their construction. Furthermore, the higher the line density of the bus network, the lower the additional travel time savings through the second station. This means that higher line density thanks to autonomous buses on the feeder on the one hand and additional train stops on the other hand do not make sense together. A combination of the two is inefficient. The addition of a second station in a given town is only meaningful, if there is a high number of people living or working inside the catchment area reachable by foot without the need of a feeder service. As soon as the feeder service is involved, it does not matter whether it is used for 500 m or 2 km.

Afterwards we analysed **to what extent stations could be cancelled while passengers are required to travel to the next down-stream station**. It turns out that the stations most likely to be suitable for cancellation are located on railway lines with comparably low speeds, towns far away from the station and low current spacing between stations. In return, lines having a high spacing between stations already now are less suitable for possible cancellation. With a car-based feeder system, the spacing-threshold below which cancellation is suitable is higher (in absolute values) than for a bus-based feeder.

> In this context it is very important to note that lines where capacity gains for long-distance and freight traffic achievable through the acceleration of local trains would be desirable are the ones that are the least likely for cancellation: their infrastructure-wise permitted speed is often comparably high (thanks to the requirements of long-distance traffic) and the spacing between stations is likewise as few new stops have been added in recent

> years. On the opposite side of the spectrum, we have those lines where cancellation is the most likely to be suitable: those with low speeds and high station densities. However, these happen to be those lines where only regional traffic runs and capacity gains for long-distance or freight traffic are not an issue. In other words: where capacity gains are desirable, cancellation is less suitable; where cancellation is suitable, capacity gains are not required.

9.2 Conclusions from the case studies

The analysis of the three corridors part of the **case studies** yields the following, general conclusions. For the locally specific results, the reader is referred to chapter-section 8.3.

- In general, stations are well located (with regard to the optimization of travel times) with respect to the town they are meant to serve (equally valid for both types of feeders). Only in very few cases, a relocation (sometimes together with a merger) is suitable.

- The availability of the required land for the establishment of an interchange facility between rail and a car-based feeder system can be problematic. In many cases, the required surface is more than 5'000 m^2, in some cases even as much as 10'000 m^2. Often such a piece of land is not easily available around the current station. The first alternative would be the construction of an underground or on-bridge interchange facility which increases costs tremendously. The second option is the establishment of a car-based feeder interchange on a free piece of land outside the town centre. On the one hand this implies a relocation away from the optimal location. On the other hand, it involves the use of unbuilt agricultural land. The latter is a politically highly sensitive topic in Switzerland.

> **It is highly questionable whether any of those two alternatives would be politically feasible. It can be expected that the concerned municipalities would oppose such projects. One should only remember the level of commotion caused by other transport-related projects in the past.**

9.3 Answering the main research question

The main research question of this project reads as follows:

> **What are the optimal number, location and design of railway stations along lines in commuting zones of agglomerations in a transport system with autonomous cars, shared feeder services and buses? Which will be the requirements given by land use and consequences for the latter?**

In the light of the previous findings we can say that:

- The optimal number of stations is generally one per town. Additional stations within the same town are only purposeful if they can be reached by walking by many people. Cancelling stations in general leads to travel time losses for the respective towns.

- The optimal station location is always downstream of the town centre. Unless we choose extreme parameter combinations of speed and built environment, it is still very close to the town centre (only a few hundred meters away). This is equally valid for both types of autonomous feeders, regardless of their exact nature, with the optimal location for a car-based feeder being a little further downstream than the one for a bus-based feeder.

  The further the town stretches away from the railway line, the further downstream the optimal location of the station. This is both valid for railway lines passing outside the towns they serve, as well as for towns which are perpendicular to the railway line.

- If stations are meant to serve as an interchange between rail and a car-based feeder, space requirements are high, as the drop-off facility receiving the arriving cars is not designed for the average inflow but for the maximum peak inflow which can be as high as the saturation flow on the access roads.

- The space required for such a rail-car interchange is not easily available in most towns. Either expensive underground or on-bridge facilities are needed, or the station is relocated outside the town, where unbuilt, agricultural land exists. However, this is likely to create conflicts, as previous projects in the field of transportation have shown. It can be doubted whether such projects of rail-car interchange facilities on agricultural land are politically feasible.

- A bus-based feeder system does not have the same land use requirements, as it involves far less vehicles and their number is precisely known in advance. An augmentation of the line density of bus-feeder networks does not reduce travel times in a significant way, but it can considerably shorten access/egress ways. Together with an extension of service times (up to a 24/7 service), its quality for passengers can come very close to the one of a car-based feeder. The temporal bundling of demand dictated by the train schedule strongly favours bundling of demand on the feeder, too.

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A1   Appendix 1: Results of generic test cases

Appendix A1.1: Comparing Car vs Bus

Mode	Case	MultiSt.	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed bus [km/h]	Mode	Case	MultiSt.
			Input					Output		Output difference		Output		Input							
Car	Case 0	No	Circular	center	medium	80	30	-300	0.09	-200	0.7	-500	0.79	Circular	center	medium	80	20	Bus	Case 0	No
Car	Case 0.1	No	Circular	center	small	80	30	-100	0.05	-100	0.37	-200	0.42	Circular	center	small	80	20	Bus	Case 0.1	No
Car	Case 0.2	No	Circular	center	medium	80	30	-200	0.08	-300	0.53	-500	0.61	Circular	center	medium	80	20	Bus	Case 0.2	No
Car	Case 0.3	No	Circular	center	large	80	30	-400	0.16	0	-0.03	-400	0.13	Circular	center	large	80	20	Bus	Case 0.3	No
Car	Case 1.0	No	Parallel	center	medium	80	30	-600	0.22	200	-0.08	-400	0.14	Parallel	center	medium	80	20	Bus	Case 1.0	No
Car	Case 1.1	No	Parallel	center	small	80	30	-400	0.13	200	-0.04	-200	0.09	Parallel	center	small	80	20	Bus	Case 1.1	No
Car	Case 1.2	No	Parallel	center	large	80	30	-900	0.33	300	-0.12	-600	0.21	Parallel	center	large	80	20	Bus	Case 1.2	No
Car	Case 2.0	No	Perpendicular	center	medium	80	30	-400	0.14	200	-0.05	-200	0.09	Perpendicular	center	medium	80	20	Bus	Case 2.0	No
Car	Case 2.1	No	Perpendicular	center	small	80	30	-200	0.08	100	-0.03	-100	0.05	Perpendicular	center	small	80	20	Bus	Case 2.1	No
Car	Case 2.2	No	Perpendicular	center	large	80	30	-600	0.21	200	-0.07	-400	0.14	Perpendicular	center	large	80	20	Bus	Case 2.2	No
Car	Case 3.0	No	Circular	tangent	medium	80	30	-300	0.11	100	-0.02	-200	0.09	Circular	tangent	medium	80	20	Bus	Case 3.0	No
Car	Case 3.1	No	Circular	tangent	small	80	30	-200	0.05	100	-0.01	-100	0.04	Circular	tangent	small	80	20	Bus	Case 3.1	No
Car	Case 3.2	No	Circular	tangent	large	80	30	-600	0.22	200	-0.06	-400	0.16	Circular	tangent	large	80	20	Bus	Case 3.2	No
Car	Case 4.0	No	Circular	outlier	medium	80	30	-500	0.2	100	-0.07	-400	0.13	Circular	outlier	medium	80	20	Bus	Case 4.0	No
Car	Case 4.1	No	Circular	outlier	small	80	30	-300	0.1	100	-0.04	-200	0.06	Circular	outlier	small	80	20	Bus	Case 4.1	No
Car	Case 4.2	No	Circular	outlier	large	80	30	-1100	0.39	400	-0.13	-700	0.26	Circular	outlier	large	80	20	Bus	Case 4.2	No
Car	Case 5.0	No	Parallel	tangent	medium	80	30	-600	0.24	200	-0.10	-400	0.14	Parallel	tangent	medium	80	20	Bus	Case 5.0	No
Car	Case 5.1	No	Parallel	tangent	large	80	30	-1000	0.37	400	-0.16	-600	0.21	Parallel	tangent	large	80	20	Bus	Case 5.1	No
Car	Case 6.0	No	Parallel	outlier	medium	80	30	-800	0.28	500	-0.20	-300	0.08	Parallel	outlier	medium	80	20	Bus	Case 6.0	No
Car	Case 6.1	No	Parallel	outlier	small	80	30	-400	0.16	200	-0.07	-200	0.09	Parallel	outlier	small	80	20	Bus	Case 6.1	No
Car	Case 7.0	No	Perpendicular	tangent	medium	80	30	-500	0.19	300	-0.13	-200	0.06	Perpendicular	tangent	medium	80	20	Bus	Case 7.0	No
Car	Case 7.1	No	Perpendicular	tangent	large	80	30	-900	0.33	600	-0.21	-300	0.12	Perpendicular	tangent	large	80	20	Bus	Case 7.1	No
Car	Case 8.0	No	Perpendicular	outlier	medium	80	30	-800	0.3	500	-0.18	-300	0.12	Perpendicular	outlier	medium	80	20	Bus	Case 8.0	No
Car	Case 8.1	No	Perpendicular	outlier	small	80	30	-500	0.16	300	-0.10	-200	0.06	Perpendicular	outlier	small	80	20	Bus	Case 8.1	No
Car	Case 9.0	No	Circular	center	medium	50	50	-700	0.41	-100	1.11	-800	1.52	Circular	center	medium	50	30	Bus	Case 9.0	No
Car	Case 9.1	No	Circular	center	small	50	50	-400	0.2	0	0.66	-400	0.86	Circular	center	small	50	30	Bus	Case 9.1	No
Car	Case 9.2	No	Circular	center	large	50	50	-1300	0.72	-200	0.46	-1500	1.18	Circular	center	large	50	30	Bus	Case 9.2	No
Car	Case 10.1	No	Parallel	center	medium	50	50	-1600	0.96	700	-0.41	-900	0.55	Parallel	center	medium	50	30	Bus	Case 10.1	No
Car	Case 10.2	No	Perpendicular	center	medium	50	50	-1100	0.62	600	-0.28	-500	0.34	Perpendicular	center	medium	50	30	Bus	Case 10.2	No
Car	Case 11.1	No	Circular	tangent	medium	50	50	-1000	0.53	400	-0.14	-600	0.39	Circular	tangent	medium	50	30	Bus	Case 11.1	No
Car	Case 11.2	No	Circular	outlier	medium	50	50	-1800	0.95	900	-0.42	-900	0.53	Circular	outlier	medium	50	30	Bus	Case 11.2	No
Car	Case 12.1	No	Parallel	tangent	medium	50	50	-1800	1.03	600	-0.46	-1200	0.57	Parallel	tangent	medium	50	30	Bus	Case 12.1	No
Car	Case 12.2	No	Parallel	outlier	medium	50	50	-2300	1.29	900	-0.73	-1400	0.56	Parallel	outlier	medium	50	30	Bus	Case 12.2	No
Car	Case 12.3	No	Perpendicular	tangent	medium	50	50	-2200	1.02	1700	-0.74	-500	0.28	Perpendicular	tangent	medium	50	30	Bus	Case 12.3	No
Car	Case 12.4	No	Perpendicular	outlier	medium	50	50	-3100	1.5	2200	-1.00	-900	0.5	Perpendicular	outlier	medium	50	30	Bus	Case 12.4	No

- optimal locations differ of more than 500 m
- TT savings of more than 1 min
- cases with irregularities (Bus-circular-center, see report for details)

Appendix A1.2: Influence of the position of the railway line

Mode	Case	MultiSt.	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed bus [km/h]	Mode	Case	MultiSt.
							Input → Output			**Output difference**			**Output**					**Input**			
Car	Case 0	No	Circular	center	medium	80	30	-300	0.09	-200	0.7	-500	0.79	Circular	center	medium	80	20	Bus	Case 0	No
Car	Case 3.0	No	Circular	tangent	medium	80	30	-300	0.11	100	-0.02	-200	0.09	Circular	tangent	medium	80	20	Bus	Case 3.0	No
Car	Case 4.0	No	Circular	outlier	medium	80	30	-500	0.2	100	-0.07	-400	0.13	Circular	outlier	medium	80	20	Bus	Case 4.0	No
Car	Case 0.1	No	Circular	center	small	80	30	-100	0.05	-100	0.37	-200	0.42	Circular	center	small	80	20	Bus	Case 0.1	No
Car	Case 3.1	No	Circular	tangent	small	80	30	-200	0.05	100	-0.01	-100	0.04	Circular	tangent	small	80	20	Bus	Case 3.1	No
Car	Case 4.1	No	Circular	outlier	small	80	30	-300	0.1	100	-0.04	-200	0.06	Circular	outlier	small	80	20	Bus	Case 4.1	No
Car	Case 0.3	No	Circular	center	large	80	30	-400	0.16	0	-0.03	-400	0.13	Circular	center	large	80	20	Bus	Case 0.3	No
Car	Case 3.2	No	Circular	tangent	large	80	30	-600	0.22	200	-0.06	-400	0.16	Circular	tangent	large	80	20	Bus	Case 3.2	No
Car	Case 4.2	No	Circular	outlier	large	80	30	-1100	0.39	400	-0.13	-700	0.26	Circular	outlier	large	80	20	Bus	Case 4.2	No
Car	Case 1.0	No	Parallel	center	medium	80	30	-600	0.22	200	-0.08	-400	0.14	Parallel	center	medium	80	20	Bus	Case 1.0	No
Car	Case 5.0	No	Parallel	tangent	medium	80	30	-600	0.24	200	-0.10	-400	0.14	Parallel	tangent	medium	80	20	Bus	Case 5.0	No
Car	Case 6.0	No	Parallel	outlier	medium	80	30	-800	0.28	500	-0.20	-300	0.08	Parallel	outlier	medium	80	20	Bus	Case 6.0	No
Car	Case 1.1	No	Parallel	center	small	80	30	-400	0.13	200	-0.04	-200	0.09	Parallel	center	small	80	20	Bus	Case 1.1	No
Car	Case 6.1	No	Parallel	outlier	small	80	30	-400	0.16	200	-0.07	-200	0.09	Parallel	outlier	small	80	20	Bus	Case 6.1	No
Car	Case 1.2	No	Parallel	center	large	80	30	-900	0.33	300	-0.12	-600	0.21	Parallel	center	large	80	20	Bus	Case 1.2	No
Car	Case 5.1	No	Parallel	tangent	large	80	30	-1000	0.37	400	-0.16	-600	0.21	Parallel	tangent	large	80	20	Bus	Case 5.1	No
Car	Case 2.0	No	Perpendicular	center	medium	80	30	-400	0.14	200	-0.05	-200	0.09	Perpendicular	center	medium	80	20	Bus	Case 2.0	No
Car	Case 7.0	No	Perpendicular	tangent	medium	80	30	-500	0.19	300	-0.13	-200	0.06	Perpendicular	tangent	medium	80	20	Bus	Case 7.0	No
Car	Case 8.0	No	Perpendicular	outlier	medium	80	30	-800	0.3	500	-0.18	-300	0.12	Perpendicular	outlier	medium	80	20	Bus	Case 8.0	No
Car	Case 2.1	No	Perpendicular	center	small	80	30	-200	0.08	100	-0.03	-100	0.05	Perpendicular	center	small	80	20	Bus	Case 2.1	No
Car	Case 8.1	No	Perpendicular	outlier	small	80	30	-500	0.16	300	-0.10	-200	0.06	Perpendicular	outlier	small	80	20	Bus	Case 8.1	No
Car	Case 2.2	No	Perpendicular	center	large	80	30	-600	0.21	200	-0.07	-400	0.14	Perpendicular	center	large	80	20	Bus	Case 2.2	No
Car	Case 7.1	No	Perpendicular	tangent	large	80	30	-900	0.33	600	-0.21	-300	0.12	Perpendicular	tangent	large	80	20	Bus	Case 7.1	No
Car	Case 9.0	No	Circular	center	medium	50	50	-700	0.41	-100	1.11	-800	1.52	Circular	center	medium	50	30	Bus	Case 9.0	No
Car	Case 11.1	No	Circular	tangent	medium	50	50	-1000	0.53	400	-0.14	-600	0.39	Circular	tangent	medium	50	30	Bus	Case 11.1	No
Car	Case 11.2	No	Circular	outlier	medium	50	50	-1800	0.95	900	-0.42	-900	0.53	Circular	outlier	medium	50	30	Bus	Case 11.2	No
Car	Case 10.1	No	Parallel	center	medium	50	50	-1600	0.96	700	-0.41	-900	0.55	Parallel	center	medium	50	30	Bus	Case 10.1	No
Car	Case 12.1	No	Parallel	tangent	medium	50	50	-1800	1.03	600	-0.46	-1200	0.57	Parallel	tangent	medium	50	30	Bus	Case 12.1	No
Car	Case 12.2	No	Parallel	outlier	medium	50	50	-2300	1.29	900	-0.73	-1400	0.56	Parallel	outlier	medium	50	30	Bus	Case 12.2	No
Car	Case 10.2	No	Perpendicular	center	medium	50	50	-1100	0.62	600	-0.28	-500	0.34	Perpendicular	center	medium	50	30	Bus	Case 10.2	No
Car	Case 12.3	No	Perpendicular	tangent	medium	50	50	-2200	1.02	1700	-0.74	-500	0.28	Perpendicular	tangent	medium	50	30	Bus	Case 12.3	No
Car	Case 12.4	No	Perpendicular	outlier	medium	50	50	-3100	1.5	2200	-1.00	-900	0.5	Perpendicular	outlier	medium	50	30	Bus	Case 12.4	No

- (green) optimal locations differ of more than 500 m
- (yellow) TT savings of more than 1 min
- (pink) cases with irregularities (Bus-circular-center, see report for details)

Appendix A1.3: Influence of line density

Mode	Case	MultiSt.	Form	Pos. Railway line	Size	Line density	Optimal Location of station [m]	TT savings [min]	Max #Riders	Optimal Location of station [m]	TT savings [min]	Max #Riders	Optimal Location of station [m]	TT savings [min]	Max #Riders	Form	Pos. Railway line	Size	Line density	Mode	Case	MultiSt.
Bus	Case 0	No	Circular	center	medium	3	-500	0.79	693	-100	-0.69	18%	-600	0.1	821	Circular	center	medium	6	Bus	Case 13.0	No
Bus	Case 0.1	No	Circular	center	small	2	-200	0.42	190	-100	-0.12	9%	-300	0.3	207	Circular	center	small	4	Bus	Case 13.1	No
Bus	Case 0.3	No	Circular	center	large	6	-400	0.13	2638	100	-0.01	20%	-300	0.12	3158	Circular	center	large	12	Bus	Case 13.2	No
Bus	Case 1.0	No	Parallel	center	medium	3	-400	0.14	2005	0	0.00	20%	-400	0.14	2403	Parallel	center	medium	6	Bus	Case 14.1	No
Bus	Case 2.0	No	Perpendicular	center	medium	3	-200	0.09	2060	0	-0.01	17%	-200	0.08	2403	Perpendicular	center	medium	6	Bus	Case 14.2	No
Bus	Case 3.0	No	Circular	tangent	medium	3	-200	0.09	694	0	0.00	18%	-200	0.09	821	Circular	tangent	medium	6	Bus	Case 15.1	No
Bus	Case 4.0	No	Circular	outlier	medium	3	-400	0.13	694	0	0.00	18%	-400	0.13	822	Circular	outlier	medium	6	Bus	Case 15.2	No
Bus	Case 5.0	No	Parallel	tangent	medium	3	-400	0.14	2062	0	0.00	17%	-400	0.14	2403	Parallel	tangent	medium	6	Bus	Case 16.1	No
Bus	Case 6.0	No	Parallel	outlier	medium	3	-300	0.08	2074	100	0.04	16%	-200	0.12	2403	Parallel	outlier	medium	6	Bus	Case 16.2	No
Bus	Case 7.0	No	Perpendicular	tangent	medium	3	-200	0.06	2012	0	0.00	19%	-200	0.06	2404	Perpendicular	tangent	medium	6	Bus	Case 16.3	No
Bus	Case 8.0	No	Perpendicular	outlier	medium	3	-300	0.12	2009	0	0.00	20%	-300	0.12	2404	Perpendicular	outlier	medium	6	Bus	Case 16.4	No

optimal locations differ of more than 500 m

TT savings of more than 1 min

cases with irregularities (Bus-circular-center, see report for details)

Appendix A1.4: Influence of speed

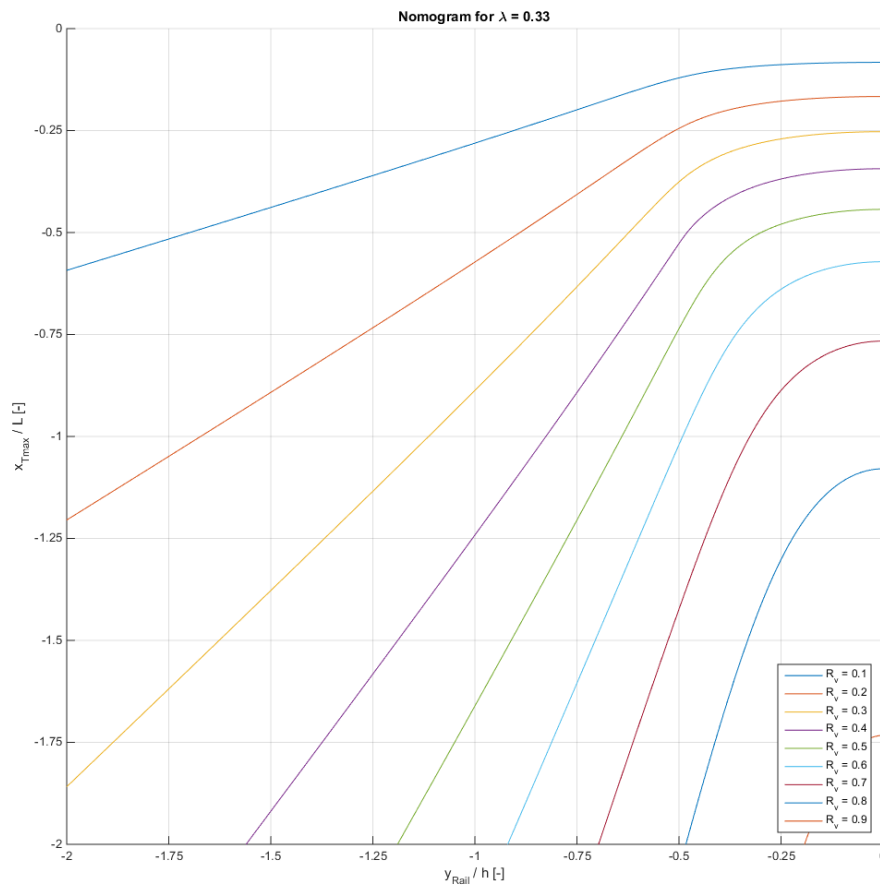| Mode	Case	MultiSt.	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Speed bus [km/h]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Optimal Location of station [m]	TT savings [min]	Form	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Speed bus [km/h]	Mode	Case	MultiSt.
							Input			Output		Output difference		Output			Input							
Car	Case 0	No	Circular	center	medium	80	30	-	-300	0.09	-400	0.32	-700	0.41	Circular	center	medium	50	50	-	Car	Case 9.0	No
Car	Case 0.1	No	Circular	center	small	80	30	-	-100	0.05	-300	0.15	-400	0.2	Circular	center	small	50	50	-	Car	Case 9.1	No
Car	Case 0.3	No	Circular	center	large	80	30	-	-400	0.16	-900	0.56	-1300	0.72	Circular	center	large	50	50	-	Car	Case 9.2	No
Car	Case 1.0	No	Parallel	center	medium	80	30	-	-600	0.22	-1000	0.74	-1600	0.96	Parallel	center	medium	50	50	-	Car	Case 10.1	No
Car	Case 2.0	No	Perpendicular	center	medium	80	30	-	-400	0.14	-700	0.48	-1100	0.62	Perpendicular	center	medium	50	50	-	Car	Case 10.2	No
Car	Case 3.0	No	Circular	tangent	medium	80	30	-	-300	0.11	-700	0.42	-1000	0.53	Circular	tangent	medium	50	50	-	Car	Case 11.1	No
Car	Case 4.0	No	Circular	outlier	medium	80	30	-	-500	0.2	-1300	0.75	-1800	0.95	Circular	outlier	medium	50	50	-	Car	Case 11.2	No
Car	Case 5.0	No	Parallel	tangent	medium	80	30	-	-600	0.24	-1200	0.79	-1800	1.03	Parallel	tangent	medium	50	50	-	Car	Case 12.1	No
Car	Case 6.0	No	Parallel	outlier	medium	80	30	-	-800	0.28	-1500	1.01	-2300	1.29	Parallel	outlier	medium	50	50	-	Car	Case 12.2	No
Car	Case 7.0	No	Perpendicular	tangent	medium	80	30	-	-500	0.19	-1700	0.83	-2200	1.02	Perpendicular	tangent	medium	50	50	-	Car	Case 12.3	No
Car	Case 8.0	No	Perpendicular	outlier	medium	80	30	-	-800	0.3	-2300	1.20	-3100	1.5	Perpendicular	outlier	medium	50	50	-	Car	Case 12.4	No
Bus	Case 0	No	Circular	center	medium	80	-	20	-500	0.79	-300	0.73	-800	1.52	Circular	center	medium	50	-	30	Bus	Case 9.0	No
Bus	Case 0.1	No	Circular	center	small	80	-	20	-200	0.42	-200	0.44	-400	0.86	Circular	center	small	50	-	30	Bus	Case 9.1	No
Bus	Case 0.3	No	Circular	center	large	80	-	20	-400	0.13	-1100	1.05	-1500	1.18	Circular	center	large	50	-	30	Bus	Case 9.2	No
Bus	Case 1.0	No	Parallel	center	medium	80	-	20	-400	0.14	-500	0.41	-900	0.55	Parallel	center	medium	50	-	30	Bus	Case 10.1	No
Bus	Case 2.0	No	Perpendicular	center	medium	80	-	20	-200	0.09	-300	0.25	-500	0.34	Perpendicular	center	medium	50	-	30	Bus	Case 10.2	No
Bus	Case 3.0	No	Circular	tangent	medium	80	-	20	-200	0.09	-400	0.30	-600	0.39	Circular	tangent	medium	50	-	30	Bus	Case 11.1	No
Bus	Case 4.0	No	Circular	outlier	medium	80	-	20	-400	0.13	-500	0.40	-900	0.53	Circular	outlier	medium	50	-	30	Bus	Case 11.2	No
Bus	Case 5.0	No	Parallel	tangent	medium	80	-	20	-400	0.14	-800	0.43	-1200	0.57	Parallel	tangent	medium	50	-	30	Bus	Case 12.1	No
Bus	Case 6.0	No	Parallel	outlier	medium	80	-	20	-300	0.08	-1100	0.48	-1400	0.56	Parallel	outlier	medium	50	-	30	Bus	Case 12.2	No
Bus	Case 7.0	No	Perpendicular	tangent	medium	80	-	20	-200	0.06	-300	0.22	-500	0.28	Perpendicular	tangent	medium	50	-	30	Bus	Case 12.3	No
Bus	Case 8.0	No	Perpendicular	outlier	medium	80	-	20	-300	0.12	-600	0.38	-900	0.5	Perpendicular	outlier	medium	50	-	30	Bus	Case 12.4	No

- optimal locations differ of more than 1000 m
- optimal locations differ of more than 500 m
- TT savings of more than 1 min
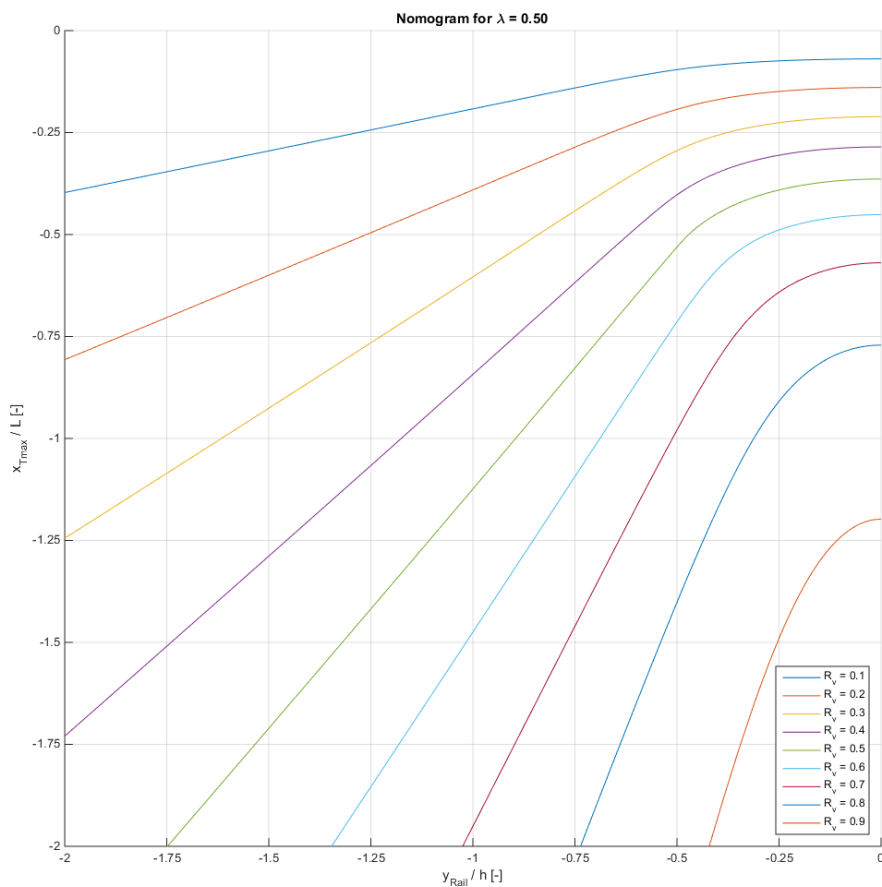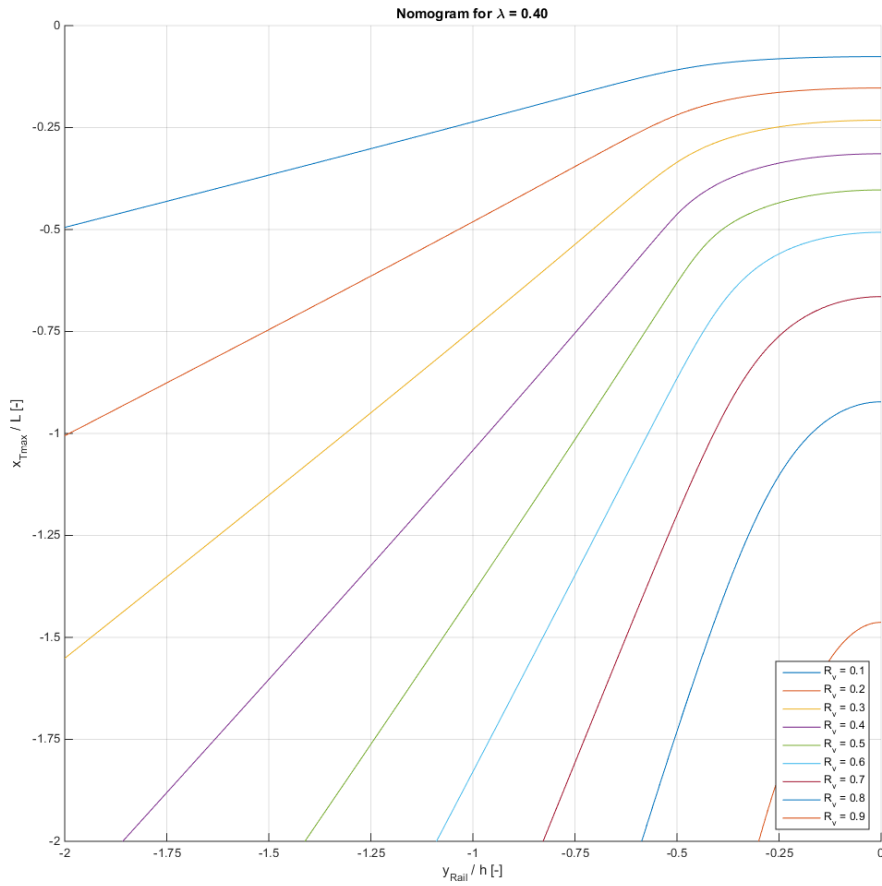- cases with irregularities (Bus-circular-center, see report for details)
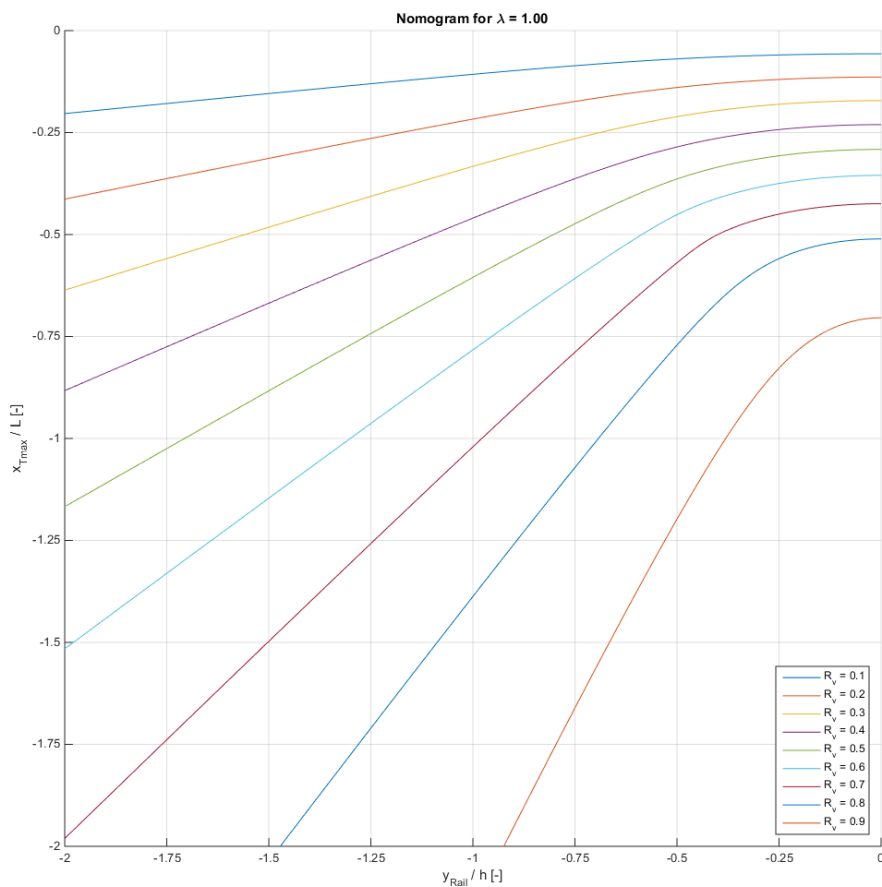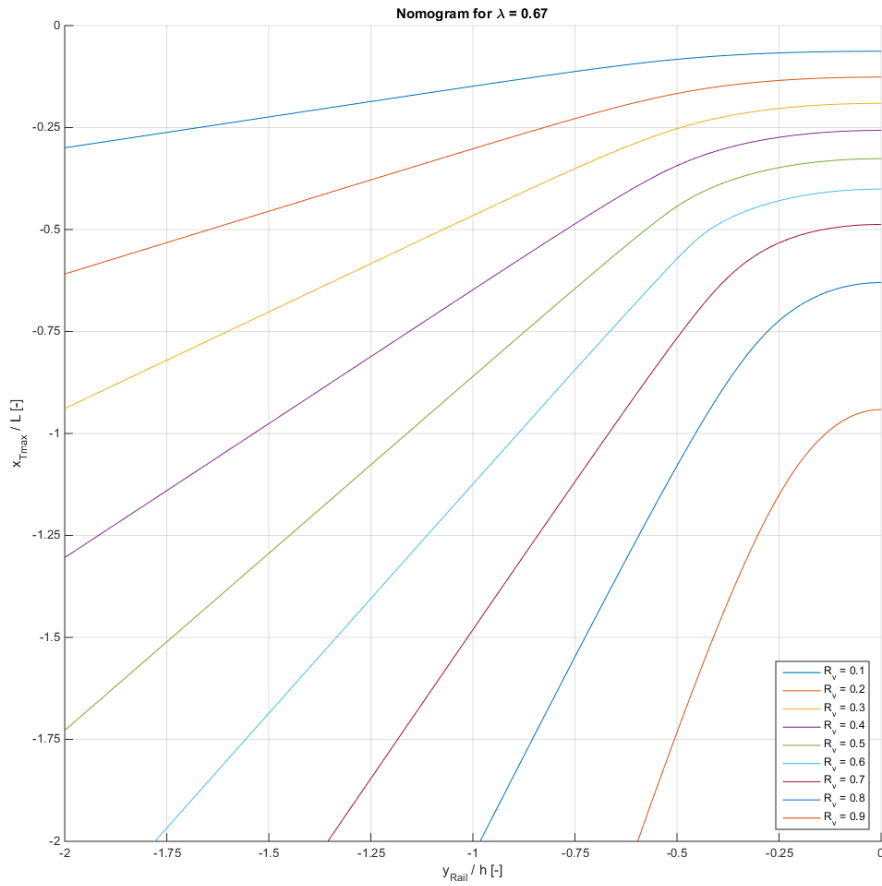
Appendix A1.5: Benefits of multiple stations

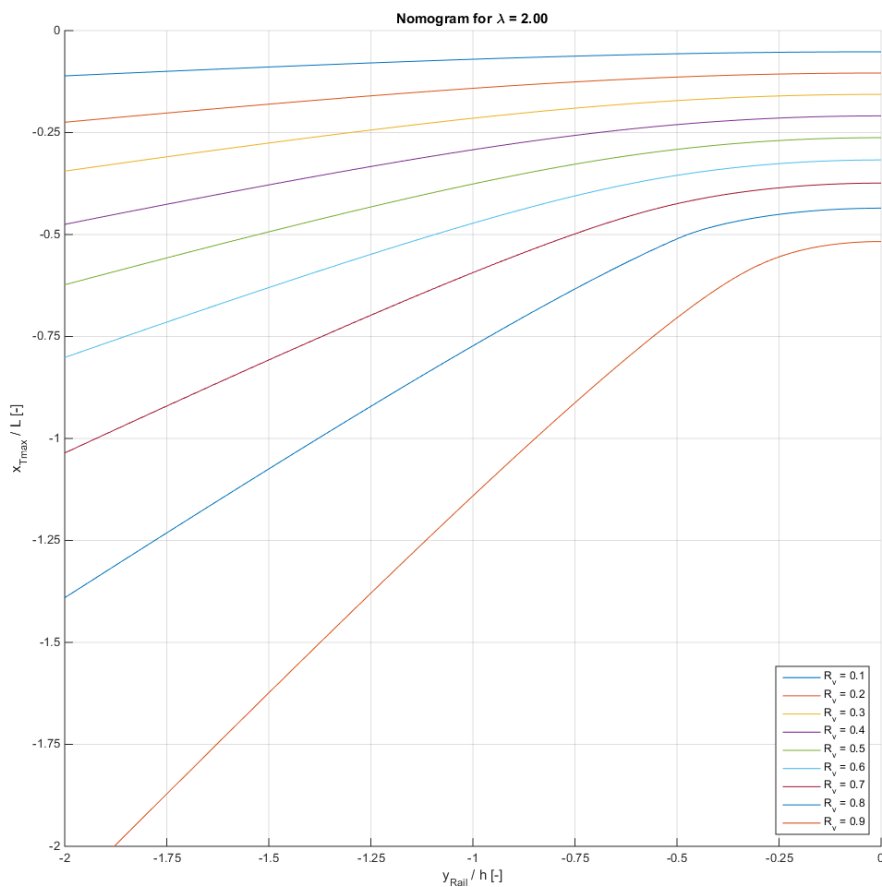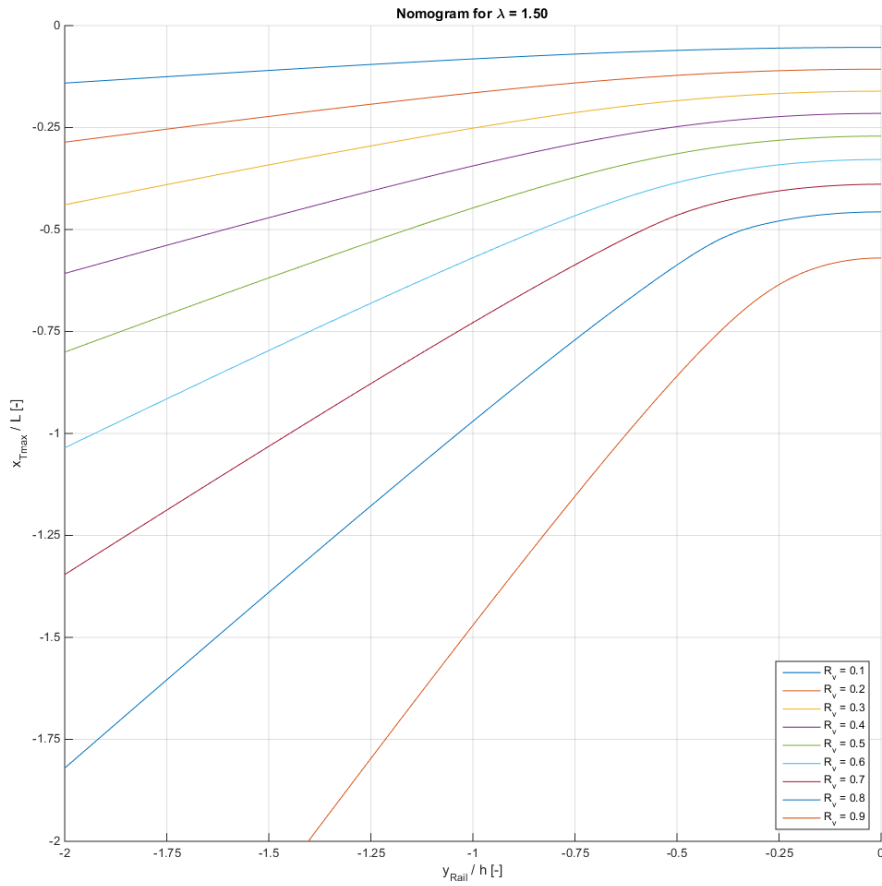| Mode	Case	MultiSt.	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Speed bus [km/h]	Line density	Max #Riders	TT savings [min]	Optimal Location of station [m]	Max #Riders	TT savings [min]	Max #Riders	TT savings [min]	Optimal Location of station [m]	Pos. Railway line	Size	Speed rail [km/h]	Speed SAC [km/h]	Speed bus [km/h]	Line density	Mode	Case	MultiSt.
					Input					Output		Output difference			Output				Input						
Car	Case 1.0	No	center	medium	80	30	-	-	-	0.22	-600		0.58	-	0.8	-1200 & 1300	center	medium	80	30	-	-	Car	Case 1.0	Yes
Car	Case 1.1	No	center	small	80	30	-	-	-	0.13	-400		0.16	-	0.29	-600 & 1000	center	small	80	30	-	-	Car	Case 1.1	Yes
Car	Case 1.2	No	center	large	80	30	-	-	-	0.33	-900		1.11	-	1.44	-1900 & 1700	center	large	80	30	-	-	Car	Case 1.2	Yes
Car	Case 5.0	No	tangent	medium	80	30	-	-	-	0.24	-600		0.38	-	0.62	-1100 & 1300	tangent	medium	80	30	-	-	Car	Case 5.0	Yes
Car	Case 5.1	No	tangent	large	80	30	-	-	-	0.37	-1000		0.66	-	1.03	-1900 & 1700	tangent	large	80	30	-	-	Car	Case 5.1	Yes
Car	Case 6.0	No	outlier	medium	80	30	-	-	-	0.28	-800		0.12	-	0.4	-1100 & 1400	outlier	medium	80	30	-	-	Car	Case 6.0	Yes
Car	Case 6.1	No	outlier	small	80	30	-	-	-	0.16	-400		0.01	-	0.17	-500 & 1100	outlier	small	80	30	-	-	Car	Case 6.1	Yes
Car	Case 10.1	No	center	medium	50	50	-	-	-	0.96	-1600		0.00	-	0.96	-1600 & 2200	center	medium	50	50	-	-	Car	Case 10.1	Yes
Car	Case 12.1	No	tangent	medium	50	50	-	-	-	1.03	-1800		0.00	-	1.03	-1800 & 1800	tangent	medium	50	50	-	-	Car	Case 12.1	Yes
Car	Case 12.2	No	outlier	medium	50	50	-	-	-	1.29	-2300		0.00	-	1.29	-2300 & -2300	outlier	medium	50	50	-	-	Car	Case 12.2	Yes
Bus	Case 1.0	No	center	medium	80	-	20	3	2005	0.14	-400	34	1.60	2039	1.74	1200 & 1200	center	medium	80	-	20	3	Bus	Case 1.0	Yes
Bus	Case 1.1	No	center	small	80	-	20	2	661	0.09	-200	0	0.63	661	0.72	-700 & 900	center	small	80	-	20	2	Bus	Case 1.1	Yes
Bus	Case 1.2	No	center	large	80	-	20	6	6729	0.21	-600	164	2.69	6893	2.9	-1700 & 1700	center	large	80	-	20	6	Bus	Case 1.2	Yes
Bus	Case 5.0	No	tangent	medium	80	-	20	3	2062	0.14	-400	68	1.93	2130	2.07	-1200 & 1200	tangent	medium	80	-	20	3	Bus	Case 5.0	Yes
Bus	Case 6.0	No	outlier	medium	80	-	20	3	2074	0.08	-300	84	1.37	2158	1.45	-1400 & 1400	outlier	medium	80	-	20	3	Bus	Case 6.0	Yes
Bus	Case 10.1	No	center	medium	50	-	30	3	2005	0.55	-900	50	0.62	2055	1.17	-1300 & 1100	center	medium	50	-	30	3	Bus	Case 10.1	Yes
Bus	Case 12.1	No	tangent	medium	50	-	30	3	2062	0.57	-1200	65	0.81	2127	1.38	-1400 & 1400	tangent	medium	50	-	30	3	Bus	Case 12.1	Yes
Bus	Case 12.2	No	outlier	medium	50	-	30	3	2074	0.56	-1400	70	0.62	2144	1.18	-1400 & 1400	outlier	medium	50	-	30	3	Bus	Case 12.2	Yes
Bus	Case 14.1	No	center	medium	80	-	20	6	2403	0.14	-400	0	1.56	2403	1.7	-1100 & 1200	center	medium	80	-	20	6	Bus	Case 14.1	Yes
Bus	Case 16.1	No	tangent	medium	80	-	20	6	2403	0.14	-400	0	1.55	2403	1.69	-1200 & 1200	tangent	medium	80	-	20	6	Bus	Case 16.1	Yes
Bus	Case 16.2	No	outlier	medium	80	-	20	6	2403	0.12	-200	0	1.17	2403	1.29	-1400 & 1400	outlier	medium	80	-	20	6	Bus	Case 16.2	Yes

Legend:
- TT savings of more than 2 min
- TT savings of more than 1 min
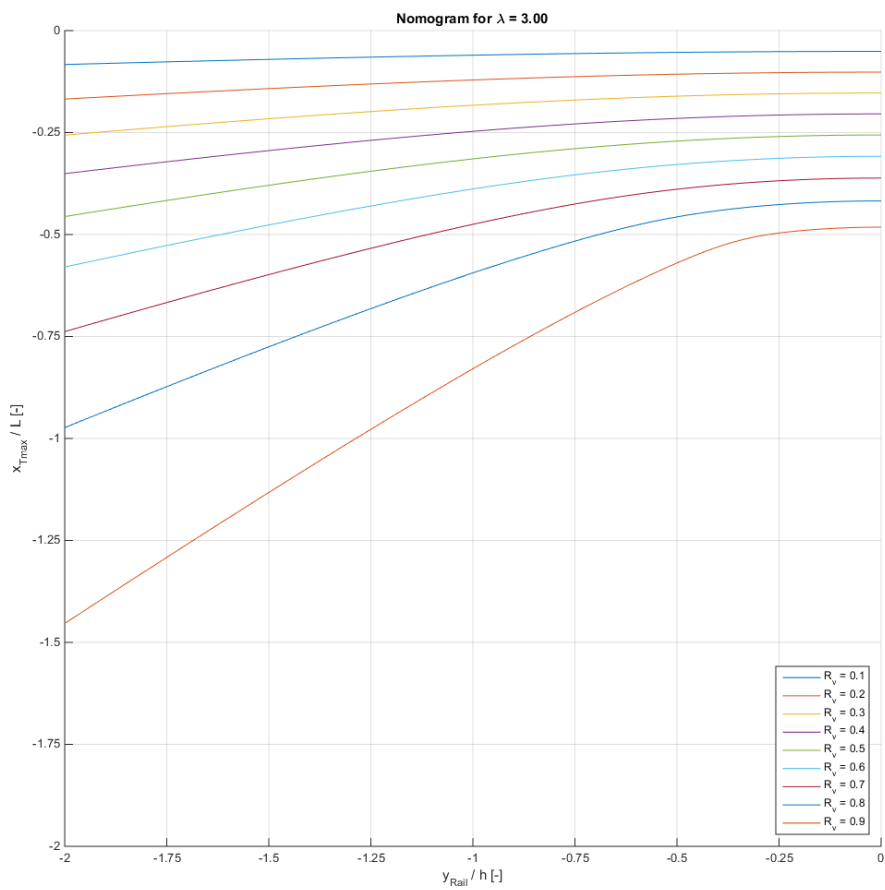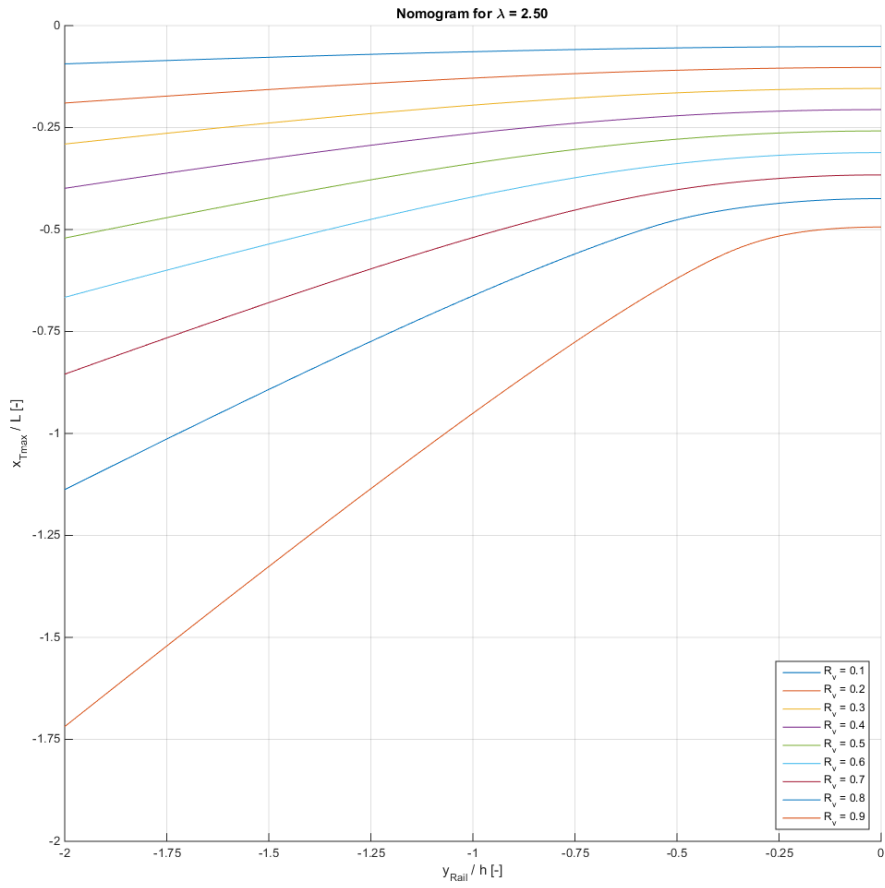- cases with irregularities (discontinuities in the generation of the bus network)

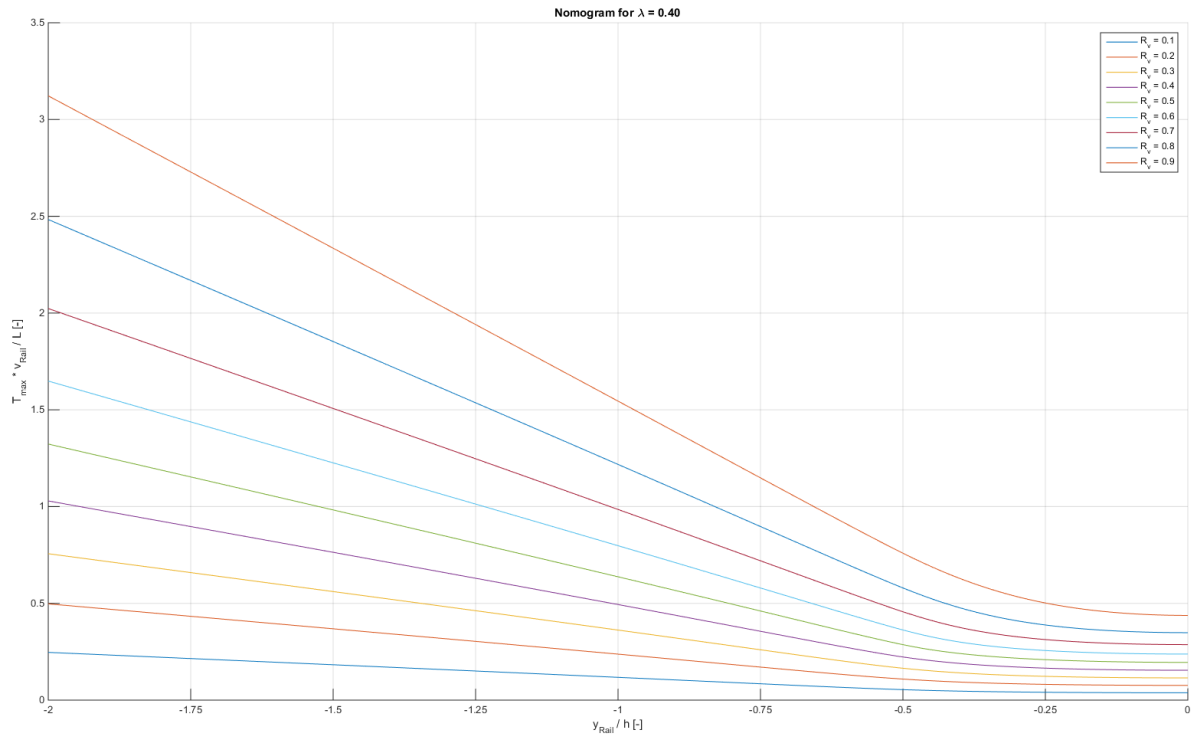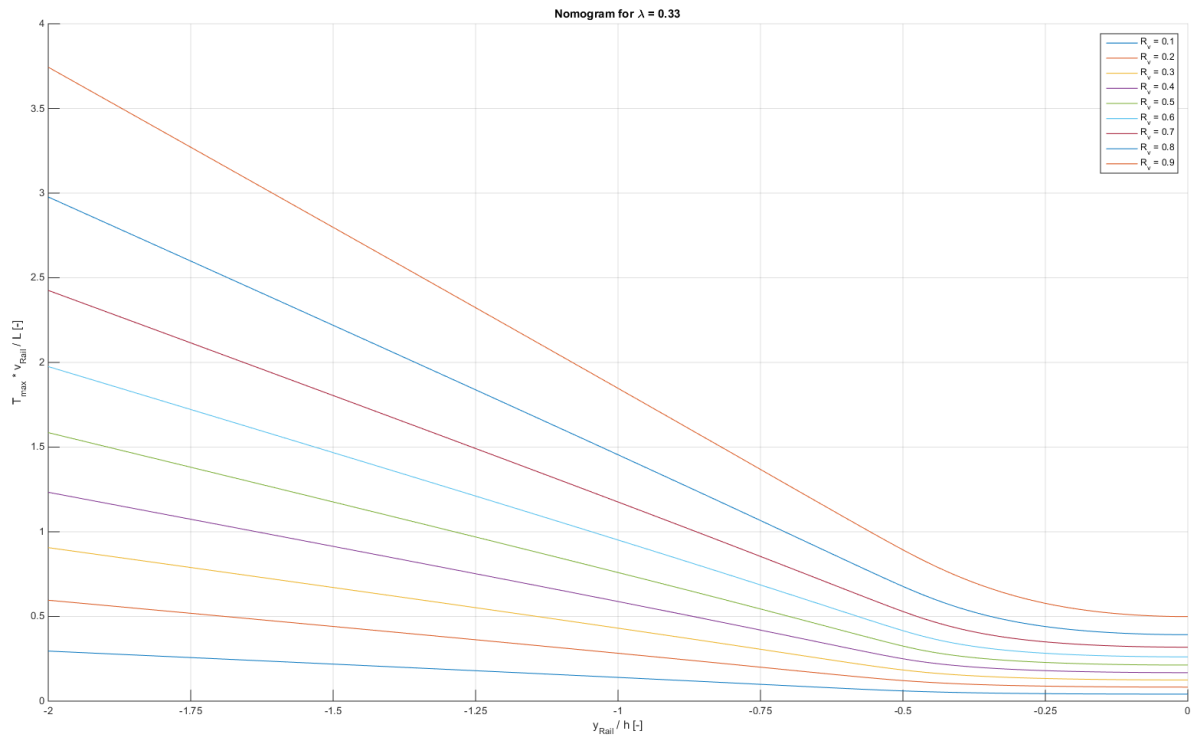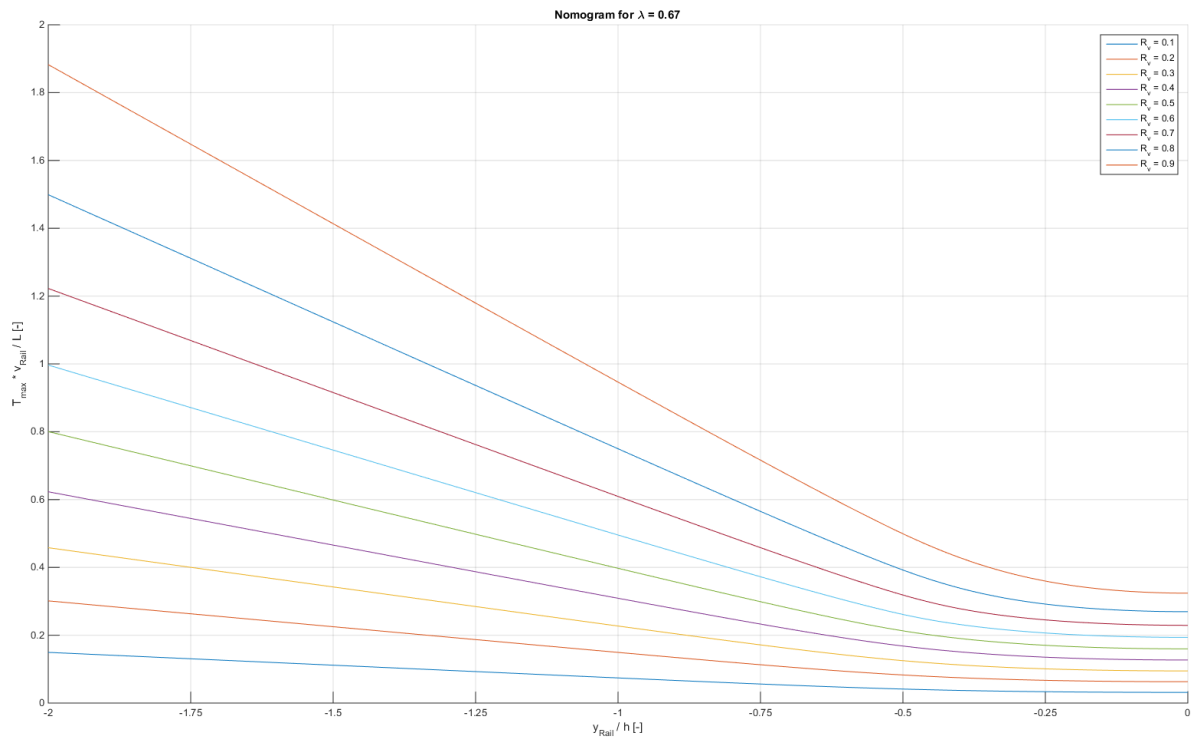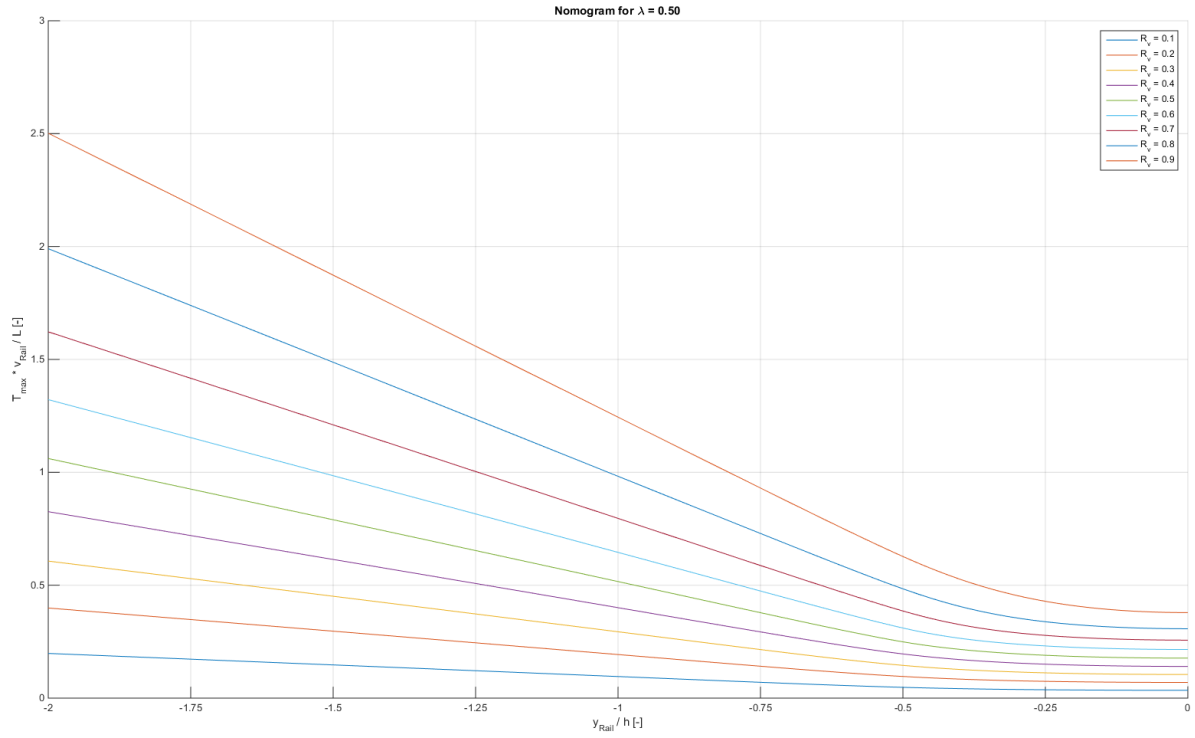# A2   Appendix 2: Nomograms for optimal station location

Nomogram for $\lambda = 0.33$

Nomogram for $\lambda = 0.40$

Nomogram for $\lambda = 0.50$

Nomogram for $\lambda = 0.67$

Nomogram for $\lambda = 1.00$

Nomogram for $\lambda = 2.50$

Nomogram for $\lambda = 3.00$

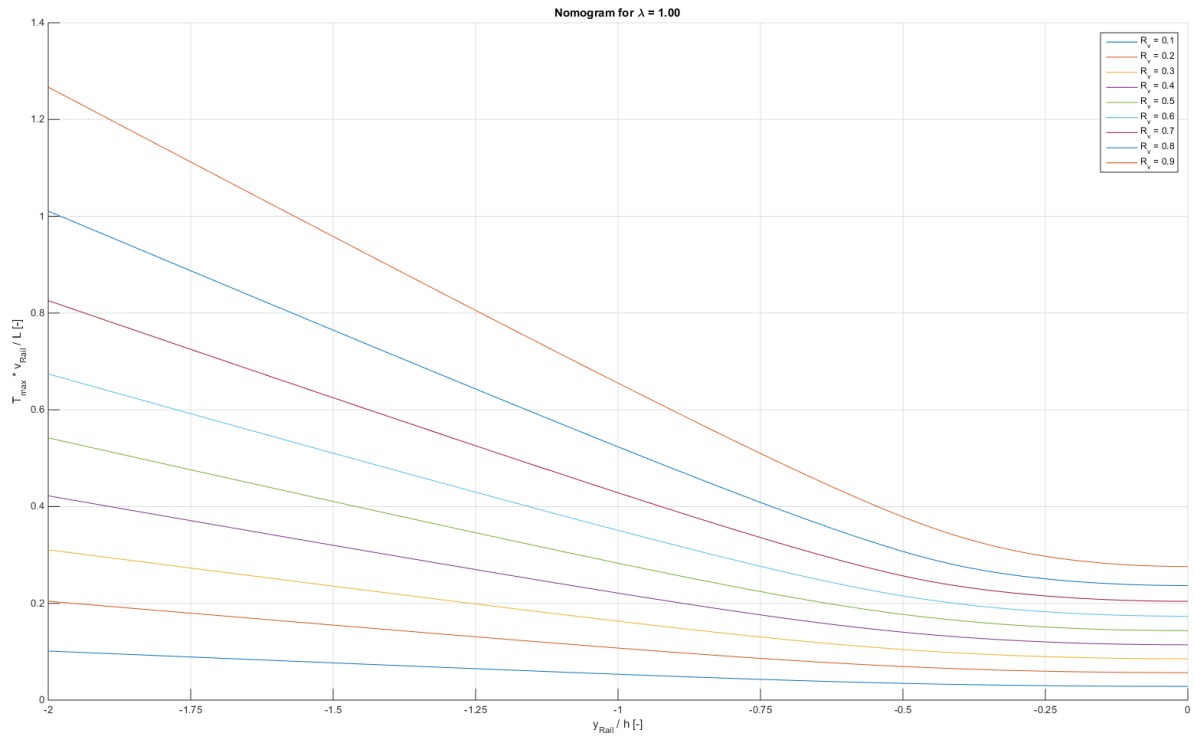# A3 Appendix 3: Nomograms for travel time savings

Nomogram for λ = 1.00

Nomogram for λ = 1.50

Nomogram for λ = 2.00

Nomogram for λ = 2.50

Nomogram for $\lambda = 3.00$
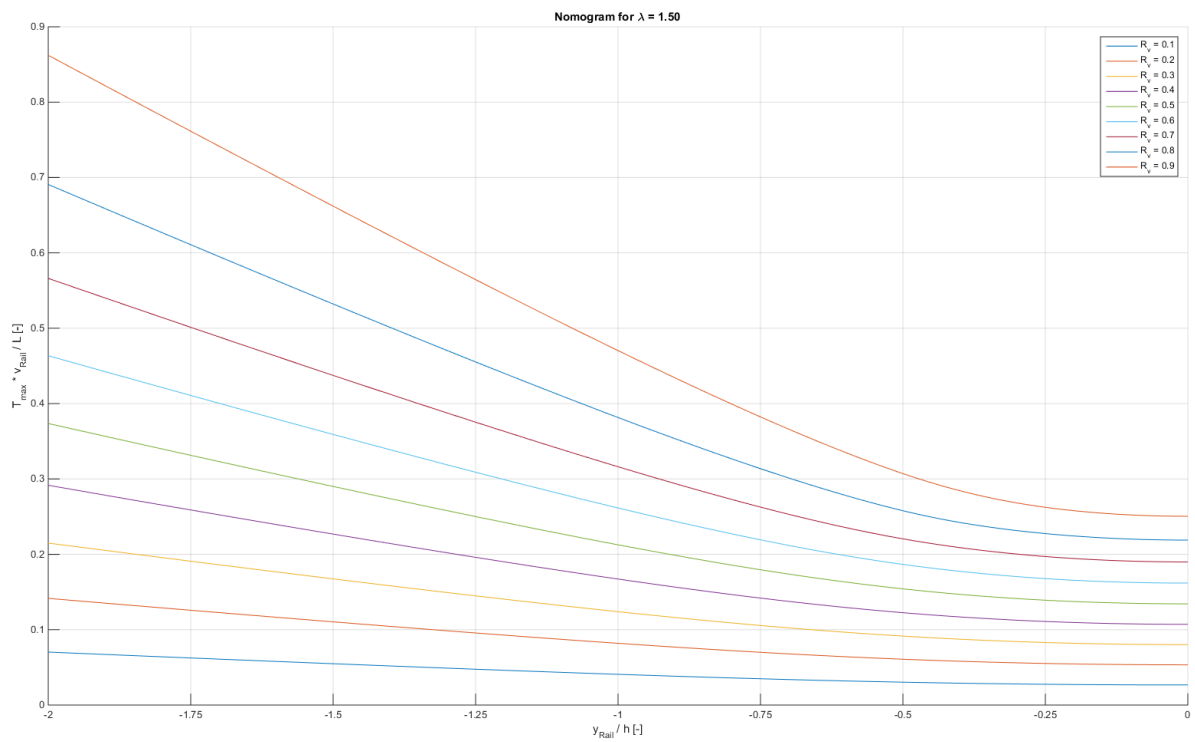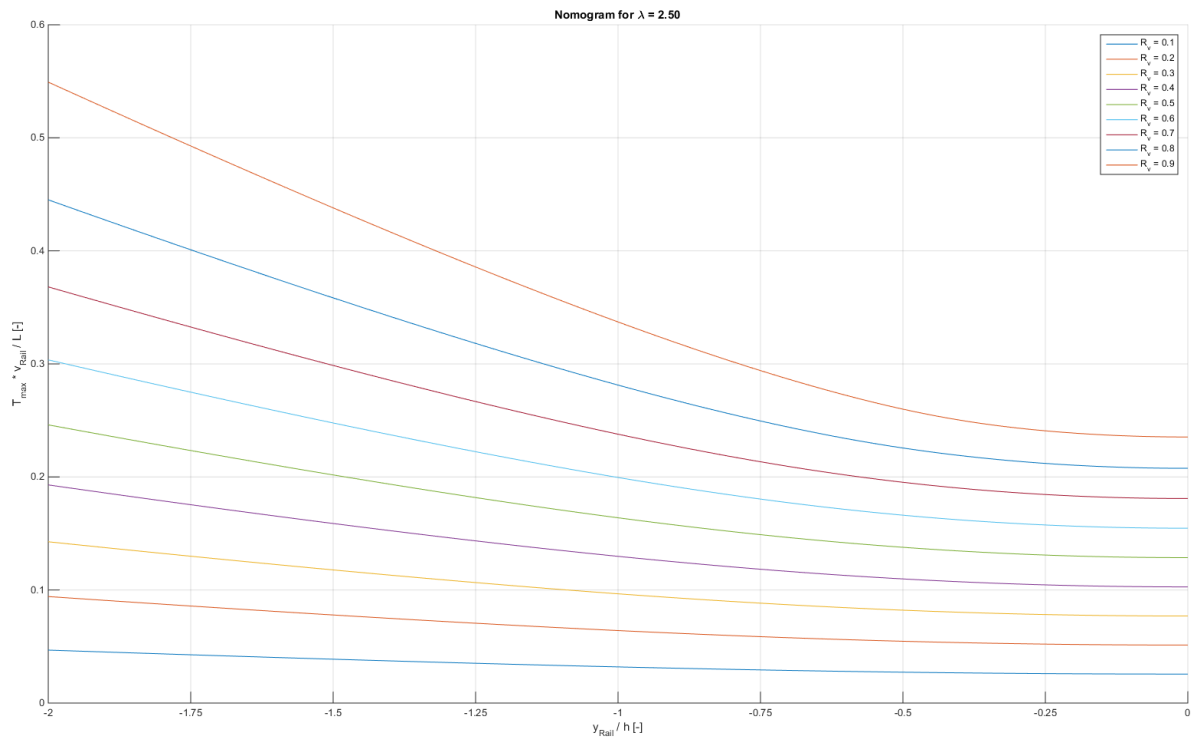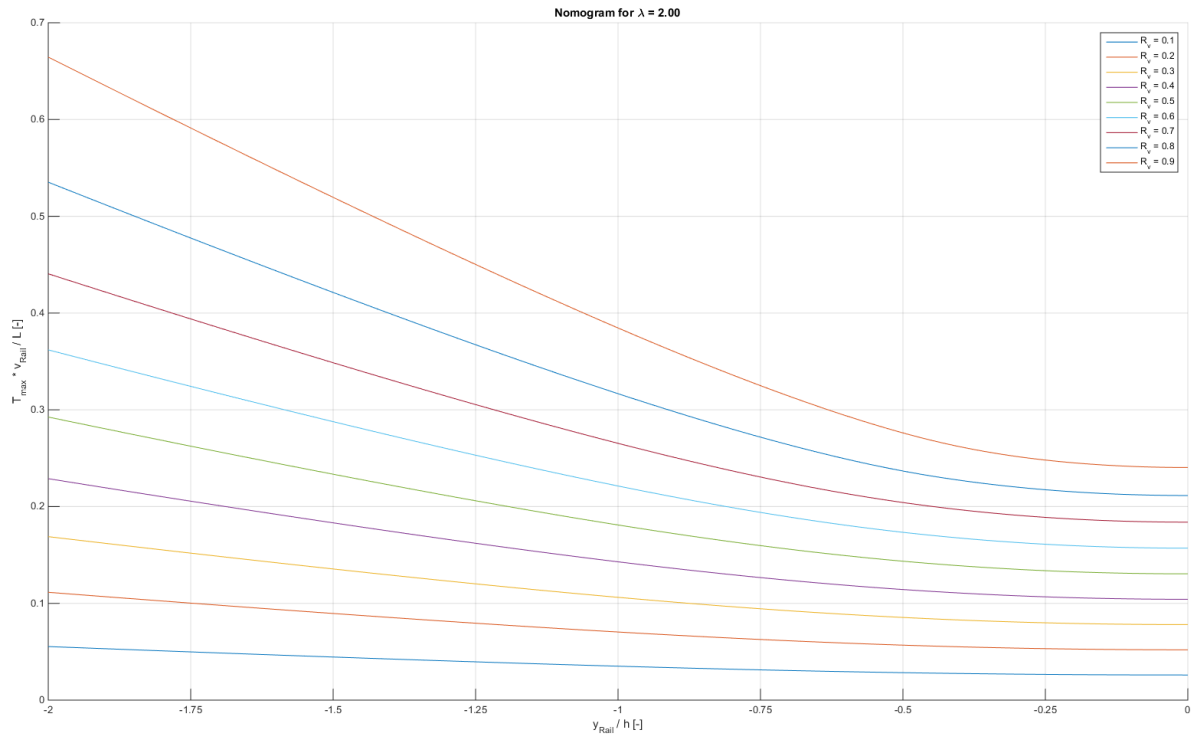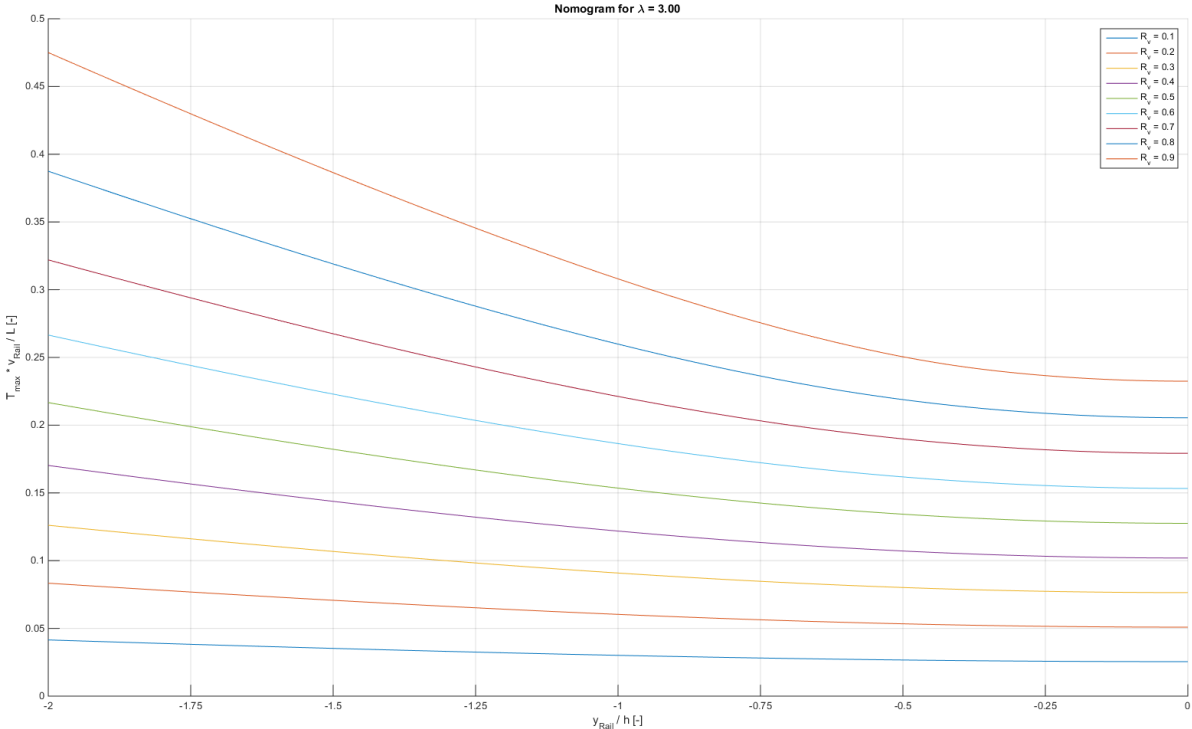
A4   Appendix 4: Selected Nomograms for break-even location for cancellation

Nomogram for λ = 1.00, K = -0.941

Nomogram for λ = 1.00, K = -1.505

Nomogram for λ = 2.50, K = -0.349

Nomogram for λ = 2.50, K = -0.558