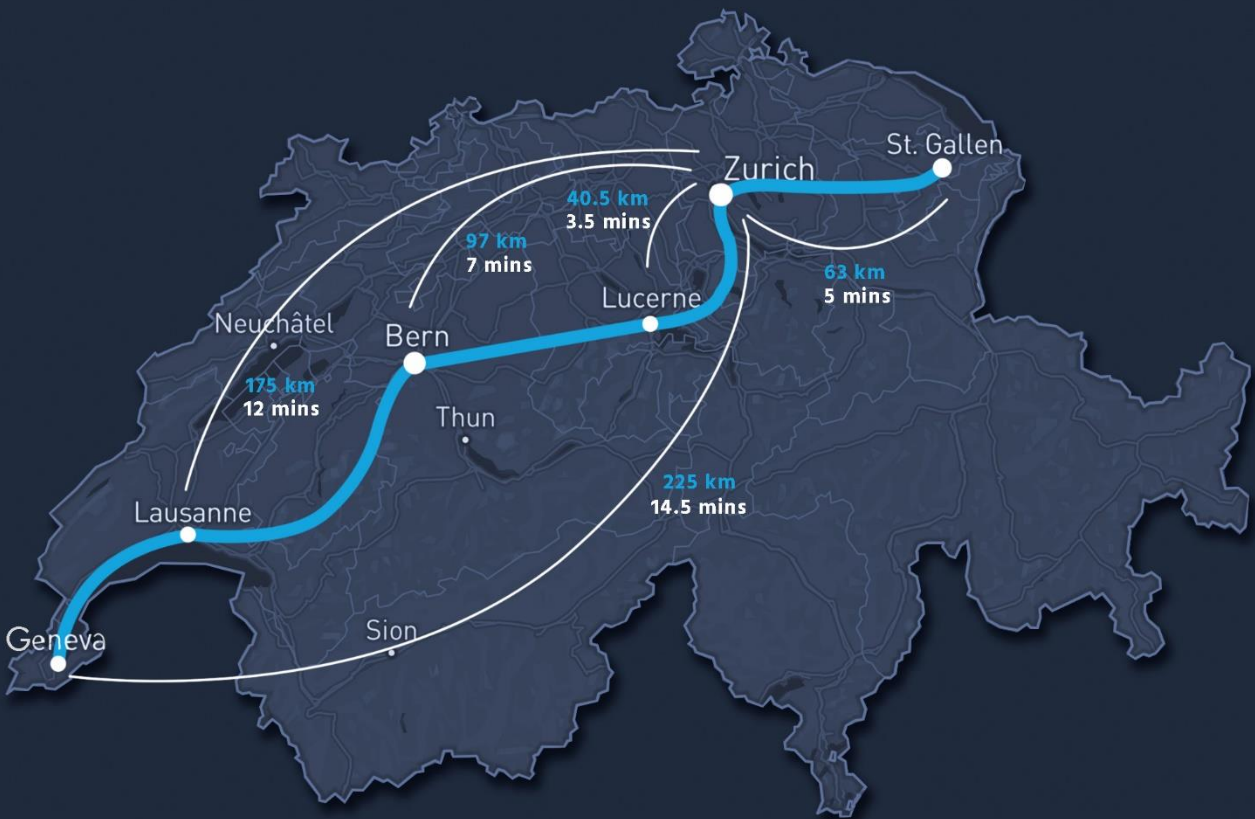
Hyperloop Network Design: The Swiss Case



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Hyperloop Network Design: The Swiss Case

By

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Executive Summary

Introduction and research objective

Increasing population and mobility demand have created many challenges including congestion on the roads, greenhouse gas emissions and pollution (Proost et al., 2011). The major contribution to these consequences comes from long and medium-distance travel. In this context, Hyperloop has emerged as a futuristic and potentially disruptive mass transit mode for medium-distance travel (SpaceX, 2013). However, existing literature does not show any detailed network design for Hyperloop. Few studies show analytical designs of the Hyperloop at a network level or a line level (Beets, 2019) (van Leeuwen, et al., 2019). None of these studies evaluates the performance of the network in terms of societal or economic gains either.

To achieve the objective of designing the Hyperloop network keeping in mind its overall impact, the following research question is proposed:

"How can a Hyperloop network be designed based upon the determinants of the cost-benefit analysis?"

The answer to the proposed research question will also help to answer a few research sub-questions with concerning to design inputs, development of a detailed method, network structure in terms of link building, defining routes, frequency and required number of vehicles; benefit to cost (B/C) ratio and sensitivity of the same.

Assumptions

To realise these findings, a few assumptions need to be made as the mode of Hyperloop is still in the conceptual phase. These assumptions mainly include the speed of the vehicle (1000 km/hr for >30 km links & 500 km/hr for <30 km link), acceleration & deceleration (0.5G), seating capacity of a vehicle (50 seats), minimum headway (90s) and non-planar bi-directional links without capacity restrictions. Also, typically scheduled transit service is assumed.

The determinants of the cost-benefit analysis (CBA) mainly include (i) infrastructure cost (ii) maintenance cost (iii) operational cost (iv) replacement cost (v) travel time savings (v) fare revenue.

Literature review

For the current study, the problem of transit network design is relevant since a typical scheduled transit service is considered. The problem of network design in the field of transport has been studied for the past five decades (Lampkin & Saalmans, 1967). Over the years, the problem has been addressed by four types of solutions (i) analytical approach (ii) mathematical formulation (iii) heuristic approach (iv) meta-heuristic approach (Kepaptsoglou et al., 2009). All the methods have their advantages and shortcomings in terms of complexity, quality of results, computational time and type of optimisation i.e. global or local. Considering the smaller size of a Hyperloop network, and because of higher speed and acceleration, a heuristic approach is selected for the network design problem.

Methodology

The overall network design process of the Hyperloop system is divided into three sequential phases. The main design steps are shown in Figure 1.

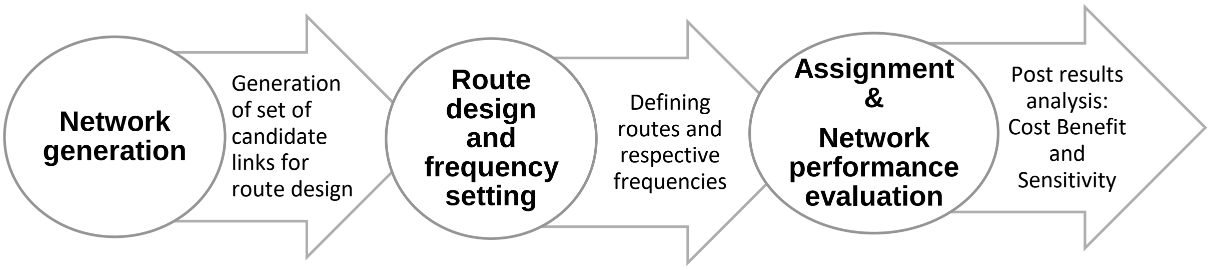


Figure 1 Hyperloop network design process

The initial phase of network generation identifies the structure of the network. It defines the links that need to be built. It works on the basis of the B/C ratio of the network. These costs are calculated based on the infrastructure cost required to build the network and the benefits are based on the in-vehicle travel time savings compared to no Hyperloop scenario. The infrastructure cost is in the form of annually-averaged cost and the demand is in the form of annual demand. The network generation phase is developed based on two approaches namely, link swapping and link deletion (Bell et al., 2019).

The link swapping approach is an additive approach. The solution algorithm in this approach starts with the minimum spanning tree (MST) of the network based on cost. This network will have the highest B/C ratio since the change in the network structure will not be able to exceed the travel time savings compared to an increase in the cost. In the following steps, the algorithm keeps adding links until the benefit to cost ratio of the network reaches below one. At the iteration when the B/C ratio drops below one, the swapping is initiated. In all the iterations, the links are chosen based on maximum direct demand of an OD pair, while the removal of a link is based on minimum assigned flow. The algorithm converges when the removed link is the same as the added link.

The second link deletion approach is a deductive approach. This algorithm is initiated with a fully connected network and it removes the links based on minimum flow on a link. This iterative process takes place until the network reaches to a B/C ratio less than one or tree structure is attained. In both the algorithms, with every iteration demand is reassigned based on the shortest paths and also the benefit to cost ratios are calculated. Both the algorithms ensure that the network would have a B/C ratio above one based upon selected cost and benefit parameters.

The next design phase is the route design and frequency setting. This solution algorithm is based upon the study by Mandl (1980). The algorithm generates a candidate set of lines on the given network and subsequently, minimises the number of transfers. The lines are identified based upon the longest shortest paths in the network. The lines ensure that the same node is not repeated in a selected line and there is a common transfer point between any given pair of lines. Once lines are identified the maximum transfer point is defined between the pair of lines. From these transfer points, the portions of the lines are changed with all possible combinations. The algorithm ends with selecting a combination of lines with the minimum number of transfers. The algorithm initially minimises the operational costs to some extent by covering the network with a minimum number of lines. And from these lines, user cost is minimised by reducing the number of transfers. Once the lines are selected the load profile for each line is plotted to determine the frequency. Subsequently, based on the frequencies and cycle time number of vehicles required are calculated.

In the next phase, the assignment procedure is performed with the regional transport network to perform the detailed CBA.

Case study & design inputs

The network is designed considering the case of Switzerland. The National Passenger Transport Model (NPVM) of Switzerland splits the national transport network in two i.e. car network and public transport (PT) network. The Swiss government offers annual or monthly subscriptions to the users of PT. Based on this, two scenarios for the year 2040 are developed i.e. the Hyperloop service being part of subscriptions and the Hyperloop service with a separate fare pricing. These scenarios are compared with the base scenario i.e. no Hyperloop scenario.

The design inputs are largely of three types (i) Stations (nodes) (ii) Costs and (iii) Demand along the travel times of existing networks.

The major cities of Switzerland with a population more than 100,000 are selected as the Hyperloop stations. These cities include: (i) Zurich (ii) Genève (iii) Bern (iv) Basel (v) Winterthur (vi) Lausanne (vii) Lucerne (viii) St. Gallen (ix) Zug (x) Baden–Brugg (xi) Fribourg (xii) Biel/Bienne. It has been assumed that the Hyperloop statins will be mounted upon the main railway stations of these cities and will have the same access time as railway stations.

The second design input of cost is derived from the literature, as is shown in Table 1. As the table shows, the infrastructure involves six elements. The costs of these elements derived from various studies are converted into Swiss Francs (CHF) taking into account the purchasing power parity exchange rate. After which, these costs are extrapolated for the year 2040 with an inflation of 1%. The maintenance cost is considered to be 10% of the average annual cost of the respective elements, while the operational cost is based upon energy and manpower cost. The user cost is derived from the weighted components of travel time in the utility functions of the respective mode. (i) Car: travel time=28.81 CHF/hr (ii) PT: access time= 28.39 CHF/hr (iii)PT: transfer time= 4.81 CHF/hr (iv) PT: no. of transfers= 3.25 CHF per transfer (v) PT: in-vehicle time=14.09 CHF/hr

The third major input is the demand for the Hyperloop network. The demand is calculated with the NPVM. The assignment procedure for both the networks car and PT networks is performed in the transport and planning software PTV Visum 13.8 (ARE, 2014). For the demand estimation, it is assumed that the Hyperloop network will be part of the existing PT network and the same beta parameters from the utility functions are applied. The demand is also estimated considering the MST network between the above-mentioned 12 nodes. The demand estimating routes are designed in such that no transfers are required within the Hyperloop network. All the lines have a headway of six minutes. The figures 2 & 3 show the estimated demand for the ‘without fare’ and ‘with fare scenario’. The travel times for the existing networks are extracted from the assignment model.

Table 1 Cost of Hyperloop system

No	Elements	Initial Investment Costs (Million CHF)	Maintenance Costs (CHF)
1	Foundation (Pylons) (per km)	9.39	53,060
	Tube (per km)	13.35	
2	Tunnel Cost (per km)	63.41	40,050
3	Station Cost (per nos.)	239.53	718,590
	Vacuum Pumps (per km)	0.17	1,020
4	Solar Panels (per km)	2.79	-
5	Propulsion System (per km)	0.47	2,820
6	Vehicles (per seat))	0.09	540
	Operational Cost		
1	Staff Cost	Station	14,779,900
		Vehicle	3,695,000
2	Energy Cost (per 100 seat-km)		1.15

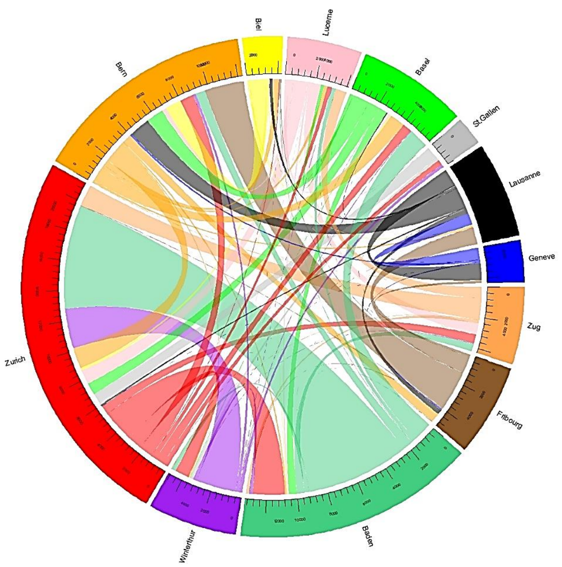


Figure 2 PT demand with Hyperloop: ‘without fare scenario’

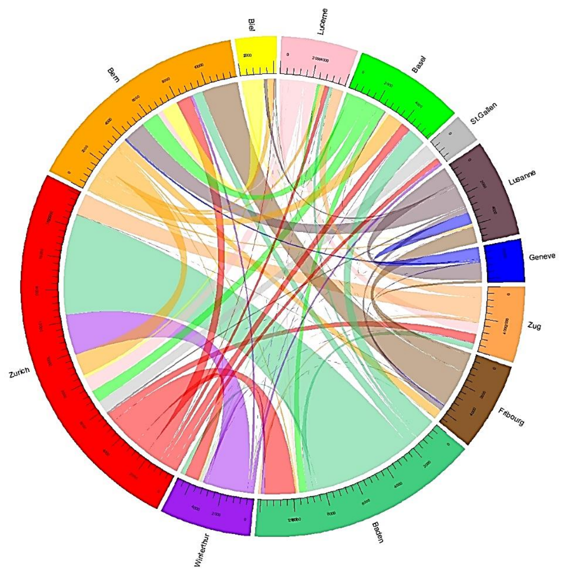


Figure 3 PT demand with Hyperloop: ‘with fare scenario’

Results & analysis
The networks generated with both approaches show the same structure. Figure 4 shows the network generated in the scenario of “without fare’ and Figure 4-2 shows network generated in the scenario of ‘with fare’. The former case has 16 links, while the latter has 15 links. This is because the latter one had lesser demand than the former one. Both the networks have a B/C ratio above one. Once the networks are generated, the routes along the frequencies are defined in the next step.

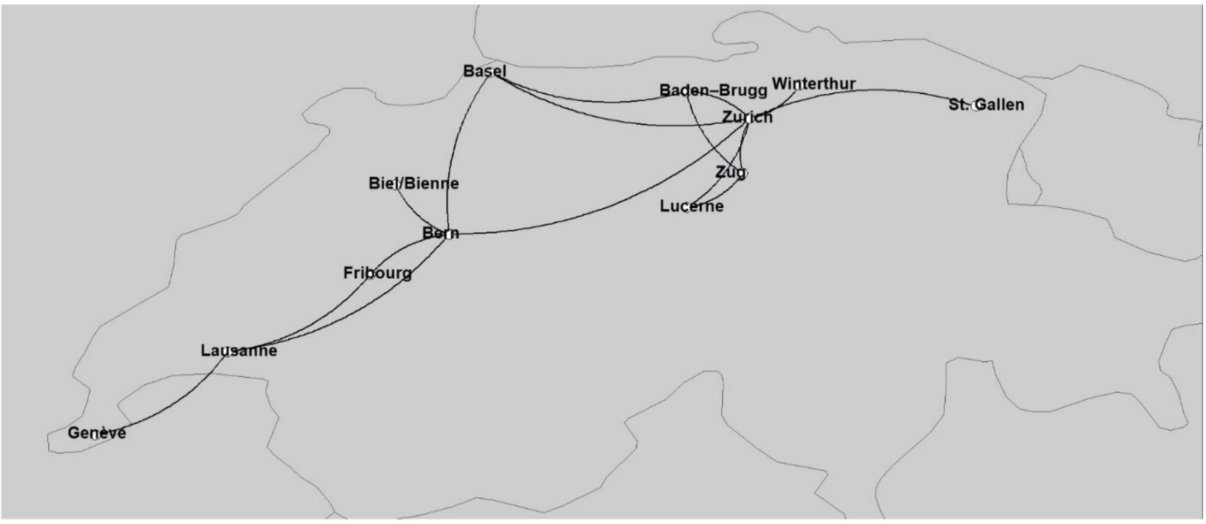


Figure 4 Network of scenario: ‘without fare’

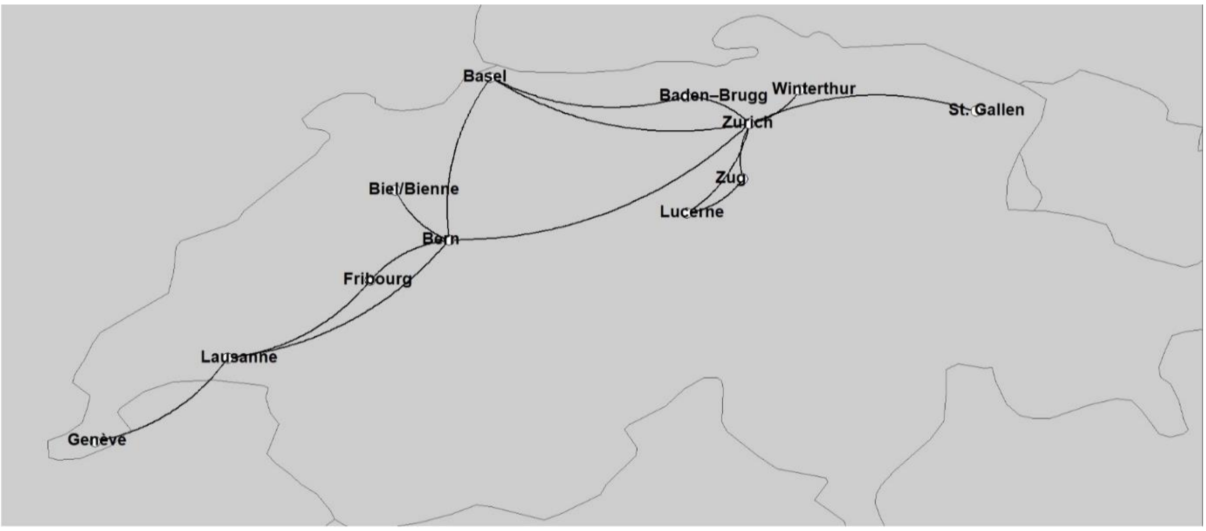


Figure 5 Network of scenario: ‘with fare’

The route design approach identified three lines on the network based on the longest shortest path of the network with Zurich being the maximum transfer point. This led to eight different combinations to evaluate. The combination with the minimum number of transfers is shown in Figure 6. The figure also shows the frequency assigned to each of the lines. These frequencies are assignment based on vehicle seating capacity and maximum flow on a line segment of the respective line. Based on these frequencies and cycle time of each line, the number of vehicles required for each case is also calculated.

After defining the routes and the frequencies, the assignment along the national transport network of Switzerland is performed to calculate the benefit to cost ratio. From the assignment model, the key numbers at network level i.e. total in-vehicle time, total access time, total number of transfers, total transfer wait times and car network travel times are extracted for the respective scenarios.

The values extracted from the assignment results are used to perform CBA and subsequently sensitivity analysis. The CBA, for the determinants costs and benefits is performed in accordance with the Swiss CBA guidelines.

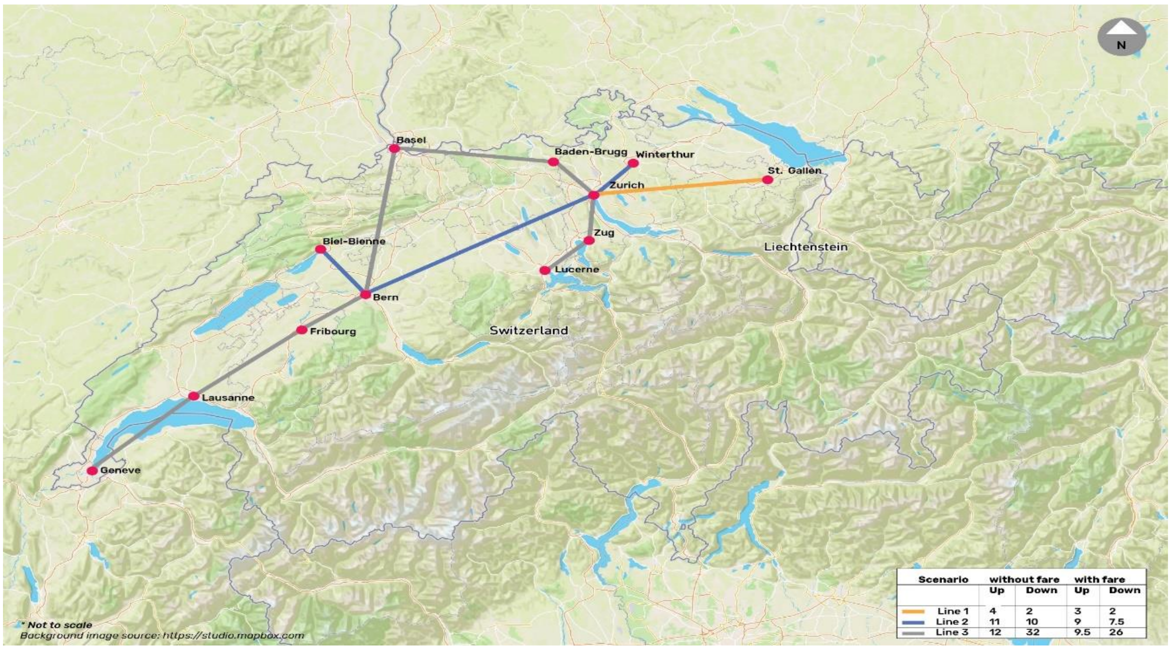


Figure 6 Geographical map of Hyperloop network along the routes

The analysis period of 50 years (2040-2089) with 2% discount rate the B/C ratio resulted in 1.69 and 1.61 for the ‘without fare’ and ‘with fare’ scenario respectively. Subsequently, the sensitivity analysis is also performed. The sensitivity analysis with the B/C ratio is performed base on three criteria: (i) Costs (ii) Value of time (VoT) (iii) Discount rate. In these three criteria, the values were changed with (10%) interval up to four cases. To perform the sensitivity analysis, the whole design process was followed in each case. The sensitivity analysis showed a linear relation between the B/C ratio and all the three criteria, and gradient change when route changes due to change in the network structure.

Conclusion & limitations

The developed procedure for network design can give an indication of how determinants of costs and benefits can be involved in the design process. Indeed, the costs and benefits considered for defining the network structure and routes are not complete. However, these can be improved by adding more costs and benefits variables, especially in terms of externalities like environment emissions, noise, accident cost and many more. This will also improve the design towards the viability of the networks.

The study has limitations in terms of inputs, design method and assignment process. The major input limitations include unavailability of actual parameters to estimate the actual demand of Hyperloop, large variations in cost estimates from different studies and limitation in estimating mode-specific demand for Hyperloop network. The overall design process is considered sequential rather than simultaneous because of the computational time. Considering a simultaneous design process for routes and network generation and re-estimating demand along the changes in the network will lead to better network design

List of Abbreviations

PT	Public Transport
TNDP	Transit Network Design Problem
B/C	Benefit to Cost
CBA	Cost-Benefit Analysis
MST	Minimum Spanning Tree
CHF	Confoederatio Helvetica Franc (Swiss Franc)
IRR	Internal Rate of Return
VoT	Value of Time
Pass-hous	Passenger X Hours: A unit to measure total service utilisation in time
NPVM	Verkehrszonen des Nationalen Personenverkehrsmodells (National Passenger Transport Model of Switzerland)
Pass-km	Passenger X kilometre: A unit to measure utilisation of network by users
Seat-km	Seat X kilometre: A unit to measure service operation
BPR function	A function developed by Bureau of Public Roads (US) to calculate the travel time based on a congestion
Beta parameters	Weights of the variables in the utility functions of mode choice

1 Introduction

The current chapter of the document introduces the research topic. The chapter starts with section 1.1 Background, describing the need for the research. Followed by section 1.2 and 1.3, describing the practices being followed in a similar research topic. After which, section 1.4 describes the research gap along with the relevance of research. This leads to the formulation of the research questions in section 1.5. After the research question is formulated, the assumptions made for the research are described in section 1.6. The chapter concludes by giving an overall outline of the thesis in section 1.7.

1.1 Background

Increasing population and mobility demand have created many challenges including congestion on the roads, greenhouse gas emissions and pollution (Proost et al., 2011). The major contribution to these consequences comes from long and medium-distance travel. The attraction towards private or individual transport is due to certain drawbacks of mass transit systems. Long egress/access time of air transport (Audenaerd et al., 2012), higher cost of rail transport (Adlera et al., 2010) and long journey time of buses (Stradling et al., 2007) are major disadvantages of mass transit systems. In this context, Hyperloop has emerged as a promising mode for medium-distance travel (SpaceX, 2013).

Hyperloop Alpha (2013), explaining the concept of Hyperloop, defines the mode as a passenger capsule, driving at very high speed under a vacuumed pressure tube with the help of magnetic levitation. The study envisaged that the Hyperloop would achieve a speed of 1220 km/hr with 1G of acceleration in a vacuumed tube of 6m diameter (SpaceX, 2013). Hyperloop has many advantages apart from high-speed travel. This includes low transportation cost, weather immunity, safety, etc. (SpaceX, 2013). It is considered as a competitive mode to high-speed rail and air transportation. With such characteristics, it is quite evident that such a mode of mass transit has the potential to change the face of transit.

Though the mode is still in the conceptual phase as of February 2019, some of the envisaged benefits like reduced infrastructure cost compared to high-speed rails, reduced overall journey time compared to air transport, and lower emissions than any other mass transit mode makes it attractive for the operators, users and authorities, respectively (SpaceX, 2013). However, at the same time, it is required that the network for such a mode be designed in a way that these benefits are maximised. Korraty et al. (2005) showed that the poor network design can be a major reason for inefficiency or unattractiveness of public transport (PT)/mass transit systems. In order to implement such a large-scale infrastructure mode, it is therefore essential that the network design is carried out in a detailed manner.

The network design problem is not limited to transportation or mass transit only. It can be seen in other fields. These fields include mainly, - communications (computers and telephonic, etc.); electric power systems and; oil, water, gas pipelines (Vitins B. J., 2014). Though the application is wider, the objective remains similar to an extent. In general, the network design problem is an optimization problem with the objective being either minimizing the function of the total cost of the network or maximising the flow i.e. throughput of the network (Bartolini, 2009). In transportation, the network design problem has been studied thoroughly for more than 50 years (Lampkin & Saalmans, The design of routes, service frequencies, and schedules for a municipal bus undertaking: a case study, 1967). While the first two decades mostly saw studies on network design for road networks, the following three decades focused on transit networks (Farahani et al., 2013). The topic of designing and optimizing transit networks is formally known as the Transit Network Design Problem (TNDP) or Transit Route Network Design Problem (TRNDP) (Kepaptsoglou & Karlaftis, 2009). Various approaches have been developed to study TNDP.

TNDP studies majorly consider bus networks, and light rail or rail networks to some extent, for case studies. In the case of bus network designs, road networks are considered as a base network on which route optimizations are performed, while the rail networks are demand-driven or developed with the objective of minimization of the overall cost. As very little research is done on Hyperloop which includes line/route-level study, applying TNDP methods to Hyperloop can contribute towards making networks efficient as well as estimating the impacts of the mode.

1.2 Related works

In terms of transit network design, a wide number of studies have been carried out for various modes (Farahani et al., 2013). It is important to notice that the network design methods for the Hyperloop do not differ much from those for typical transit services. This is because of the similarity between scheduled transit service and scheduled Hyperloop service. The only difference is in the design parameters of network design. These design parameters include speed, acceleration, the capacity of lines and vehicles, etc. Despite that, for Hyperloop or any similar high-speed mode of transport, only a couple of studies have been performed. The current section includes studies only related to Hyperloop or a similar mode.

The first study was on Swissmetro which is similar to Hyperloop in terms of being a high-speed mass transit through vacuumed pressure tubes. The initial idea of Swissmetro was conceived back in the 1970s. A company named Swissmetro[1] was established in 1992, with an idea of developing a high-speed train in Switzerland, which is underground and magnetically levitated inside vacuum pressure. The maximum speed of the train was 400km/hr (Mossi, 2002) with a vehicle-carrying capacity of 400-600 and a minimum of six minutes headway (Mossi & Rossel, 2001). The Lausanne-Geneva section was taken up for implementation and the Basel-Zurich Section with a connection to two airports was allotted for a feasibility study in 1997. Figure 1-1 shows then proposed network of Swissmetro.

The feasibility studies of Swissmetro had then estimated that the project would be able to attract 24,000 passengers between Geneva and Lausanne; and approximately 34,000 passengers between Bern and Zurich (by direct line) per day in each direction in the year 2015. The demand was estimated with the mode choice model approach using data from Swiss National Railway carrier SBB and stated preference survey. However, for the network design, no detailed optimisation had been explained in the study. The demand was found to be highly sensitive to frequencies, travel time and

[1] (RTS Radio Télévision Suisse, branch of the Swiss Broadcasting Corporation, 2010)

fares (Georg, 1999). Despite a few feasibility studies, the project could not be developed further, due to higher initial investment requirements, lack of financial support from the government and less profitability (estimated IRR of around 3%). This led to the dissolution of the company in 2010 (RTS Radio Télévision Suisse, branch of the Swiss Broadcasting Corporation, 2010).

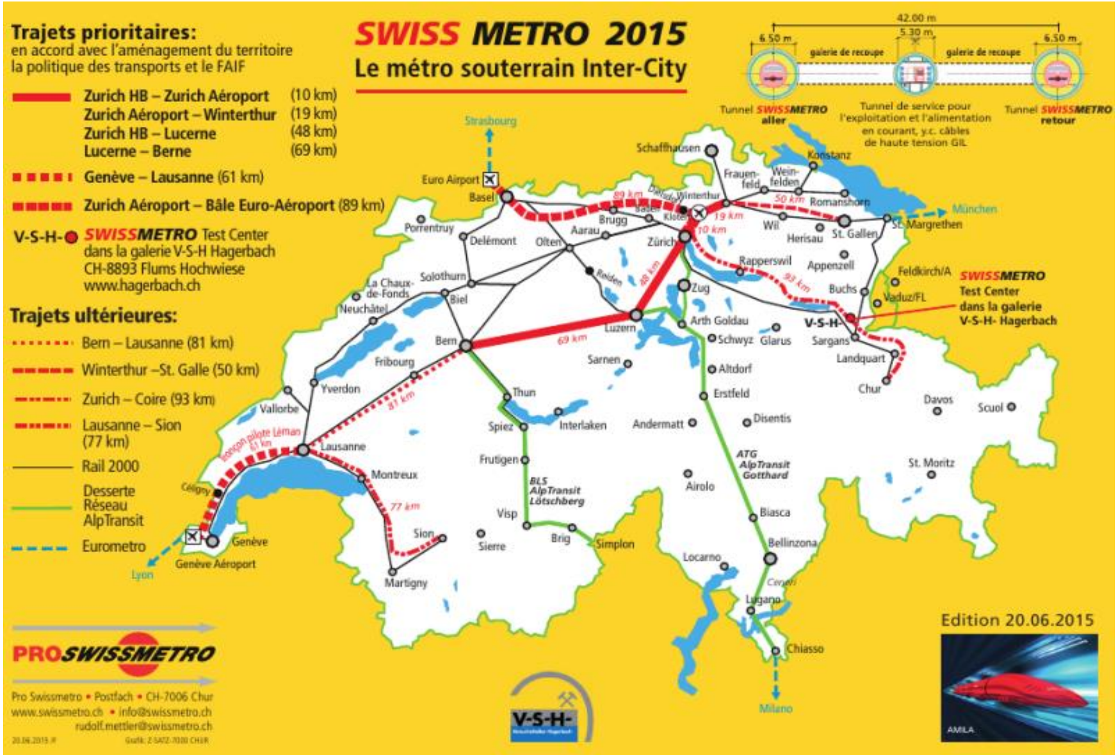


Figure 1-1 Swissmetro network (L' association Pro Swissmetro, 2015)

Usually, the cost of elevated networks is lesser compared to underground networks. Likewise, construction of an elevated Hyperloop might require lesser initial investment compared to the Swissmetro. The initial investment cost of Basel-Zurich pilot line was estimated to be 67 million CHF/km, while the operating cost for 40 years was 79 million CHF on the basis of 2002 rates (Mossi & Vuille, 2002). The Hyperloop Alpha estimates an initial investment of 10.60 million CHF/km for the infrastructure and vehicles between Los Angeles and San Francisco as per 2013 rates (SpaceX, 2013). However, a detailed comparison needs to be made as the characteristics of both modes differ in many aspects. Table 1-1 compares the technical specifications of Swissmetro and model of the Hyperloop One system (Jufer, 2018) (SpaceX, 2013). From the table, it can be observed that the Hyperloop system is a tuned version of Swissmetro in terms of technical parameters (e.g. vehicle capacity, acceleration, speed and many more).

Another similar study for the Hardt Hyperloop System was carried out by Beets A.D.J (2019). Though the study focused on the line-level approach from Berlin to Paris, it is still relevant to this research. The study applied Minimum Spanning Tree (MST)[2] between Berlin and Paris connecting major cities along the line for network generation. The author developed a mixed-integer linear problem in order to optimise capacity and fleet size for the line. A part of the study, also focused on demand estimation, for which

[2] Minimum spanning tree is a solution in graph theory that generates network in a way that overall network has minimum weight and no cycles are present in the network.

a multinomial logit model was applied. However, weights of the variables in the utility functions were chosen arbitrarily. This was mainly due to unavailability of the actual estimates or insufficient literature.

A recently published study was carried out by Delft Hyperloop. van Leeuwen, et al. (2019) developed a European Hyperloop network connecting the 48 major European cities with 51 links in their Hyperloop network. For demand estimation, the authors used the European Passenger Database of 2017 and scaled up for the year 2040. Different scenarios were assumed based on the growth in passengers. The highest growth and lowest growth were considered for the design of the network without applying a mode choice model. The direct demand for air passengers was used as Hyperloop demand. The link flows were assigned through the ratio of shortest path distance and the actual distance between the cities. Similarly, no thorough optimization was performed in the study.

Table 1-1 Technical parameters - Swissmetro and Hyperloop (Jufer, 2018) (SpaceX, 2013)

No	Parameters	Swissmetro	Hyperloop One
1	Grade level	Underground	Elevated
2	Tunnel Type & Diameter	Double tunnel, 5m	Double tube, 2.3m-3.3m
3	Vehicle Diameter	3.2m	1.38m-1.98m
4	Air Pressure	7%	1%
5	Technology for power	Magnetic levitation	Air cushion levitation
6	Guidance	Magnetic Guidance	Air cushion guidance
7	Motors	Brushless DC linear motor	Linear Induction Motor
8	Energy in Vehicle	contactless	Batteries
9	Max. Acceleration	0.13 times g	1 times g
10	Vehicle Mass	50-100 tons (200-400 pass)	15 tons for 28 pass
11	Max. Power	6MW for 400 pax	50MW for 28 pax
12	Power/kg	60 W/kg	3300 W/kg
13	Max. Speed	432 km/hr	1200 km/hr
14	Vehicle length	50-100 m	30 m
15	Min. Headway	6 min	6 min

In all the previously mentioned studies, high-speed transit networks have been developed applying MST and the flows have been assigned to the links with the shortest path. A few line-based studies also have been developed for the Hyperloop, e.g. Hyperloop Alpha (2013) between Los Angeles and San Francisco which estimates the overall cost of the lines; the pre-feasibility study of Stockholm-Helsinki also estimates the demand and the cost of the line (KPMG Sweden Inc., 2016). However, these studies do not optimise the lines or analyse the societal impacts of the system either. Thus, none of the previous studies shows any thoroughly applied optimization or detailed assessment for the Hyperloop network so far.

1.3 Problem context

In general, TNDP consists of five steps: (i) Designing routes; (ii) Setting frequencies; (iii) Developing timetables; (iv) Scheduling buses (vehicles); and (v) Scheduling drivers (Ceder & Wilson, Bus network design, 1986). These methods are largely applicable to bus networks, where the road network is a base network. However, in the case of Rail one more step is added beforehand, i.e. network generation. Network generation designs the network structure or defines the network elements i.e. nodes and links. From the perspective of TNDP, network design has been solved using different objectives that can be applied to different modal networks e.g. car, bus, rail, ferry etc. Largely, these objectives can be summarised into six categories (Black, 1995; Fielding, 1987; van Oudheusden, Ranjithan, & Singh, 1987), mapped to three further perspectives (van Nes & Bovy, Importance of objectives in urban transit network design, 2000). as shown in Table 1-2.

Table 1-2 Type of objective functions

No.	Categories	Perspective
1	User benefit maximization	User
2	Operator cost minimization	Operator
3	Total welfare maximization	User, operator and public authority
4	Capacity maximization	Operator and public authority
5	Energy conservation protection of the environment	Public authority
6	Individual parameter optimization	User

The user benefit maximization covers travel time savings, while the operator's perspective focuses on reducing, the operational costs. The user benefit maximization does not take into account the cost aspects of infrastructure or the operator. The authority, in general, is interested in increasing societal welfare, the capacity of the lines or reducing energy consumption and environment emissions. The individual parameter optimization includes line-specific transfers, transfer wait time or accessibility improvement. These objectives were categorised into three perspectives further This categorisation affects the network configuration. For example, van Nes et al. (2000) defines variables like stop spacing and line spacing for urban transit networks with users' and operators' perspectives. As for the Hyperloop system, overall societal benefits (i.e. ex-ante evaluation) needs to be assessed initially, before the implementation. And also, the category of total welfare maximization can be interpreted as minimisation of total cost i.e. infrastructural cost, operational cost and user cost. This can be considered as an objective function for the Hyperloop network design.

To design the network, based on the suitable category of objectives, a scenario-based approach (SBA) can be implemented as well. Vittins et al. (2017) in their study on "Extraction and evaluation of transportation network grammars for efficient planning applications" explain the importance of a scenario-based approach. The SBA generates different scenarios under the defined set of rules for the inputs of the model. This can be with same or different objective functions. The SBA determines the future scenario with the highest return under given budget constraints from a set of previously generated alternatives. The advantage is that a direct comparison can be made between these alternatives as the same rules will apply to all the alternatives in terms of evaluation. However, a drawback is that long-term impacts cannot be assessed, for which a separate qualitative or a quantitative analysis has to be carried out (Vittins et al., 2017). This can lead to the generation of suboptimal design for the future. Thus, in order to compare the different alternatives of Hyperloop network, SBA can be implemented as well.

1.4 Research gap

After looking at the related works and problem context, it can be observed that there is a research gap in the area of designing and impact evaluation of a new transit system such as Hyperloop. Though previous studies considered the cost for the network design, demand could not gain attention in the design process. Similarly, in the cost aspect of the network, a few attempts have been made to estimate the real cost of infrastructure by neglecting evaluation of societal impacts. The studies only show discussion of these gains or benefits of implementing such huge infrastructure qualitatively (SpaceX, 2013). This defines the research gap in the quantification of the societal benefits of the Hyperloop system. Before implementing the overall system, an ex-ante evaluation is therefore required. This study can contribute towards the methodological implementation of existing ex-ante evaluation guidelines as well as design.

The overall idea of network design is to develop a solution following a specific objective in order to perform under certain standards. This can be useful in many ways, with research in designing networks:

- Hyperloop network, providing an understanding of network structure in terms of links and nodes.
- Routes and frequency; an indication of overall travel time benefits and the fleet size required for the network can be attained.
- Required resources for the same can be estimated.

Similar to most of the ex-ante evaluation, this research can be used to evaluate the different scenarios for the same. Though this research does not contribute towards a methodology for optimisation, results can spur discussion for further improvements in terms of network parameters. Also, the effect of the Hyperloop network can be studied largely on the overall transport network, which will essentially be helpful for the ex-ante evaluation of the system and gives an indication of viability.

1.5 Research question

From the aforementioned research gap, the following research question has been derived.

“How can a Hyperloop network be designed based upon the determinants of the costs benefits analysis?”

The research question aims to find the maximum benefit-cost (B/C) ratio, which has been used as an indicator of ex-ante evaluations. The Hyperloop network scenario is compared with a no Hyperloop network scenario.

Please note that:

- The research question does not focus on the estimation of the demand in terms of the mode choice model. The estimation of demand requires detailed choice modelling. Hence, the estimation of weights variables in the utility function for Hyperloop needs to be studied separately as a more thorough research exercise.

- Making nodes variable makes the research complex. Considering the given time frame, nodes (stations) are considered to be fixed or predefined for the network.
- The overall network development is considered as a sequential procedure. This is also a pragmatic choice considering the limitation of computational time. Figure 1-2 shows the procedure for the overall network design, which can be divided into three steps. The first step 'Network Generation' defines the links between the nodes. Further, the second step defines the routes and frequency for the network, while the third step performs the detailed assessment of the network designs.

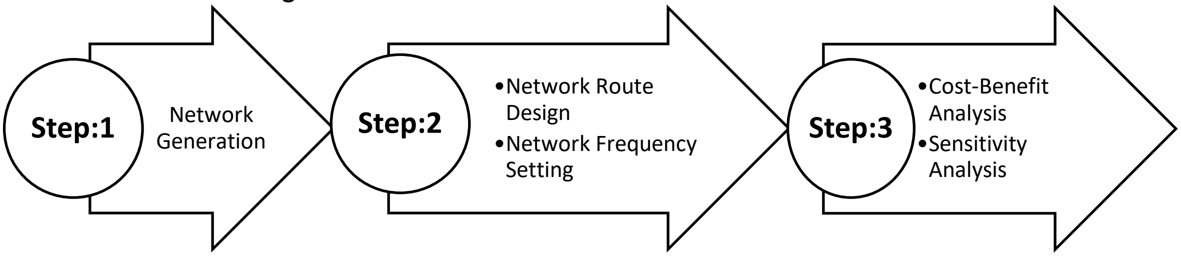


Figure 1-2 Research flow

Considering the overall process of network design, the sub-questions in this study can be summarised as below.

1. *What are the inputs required for the network design of a Hyperloop system?*
2. *What are the methods to design/optimise transit networks such as Hyperloop?*
3. *What is the feasible set of links in a Hyperloop network with respect to benefit to cost (B/C) ratio?*
4. *Which is the optimal set of routes for the Hyperloop network generated in the previous sub research question? What are the frequencies and number of vehicles required for the respective lines?*
5. *What is the B/C ratio of the Hyperloop network generated in the previous sub-research question?*
6. *To what extent is the B/C ratio of the Hyperloop network sensitive to its design inputs?*

Sub-research question one is directed towards the input preparation for the overall design process. Sub-research question two is a methodological question. This tries to define the method to answer the main research question from the literature review. Sub-research question three is part of network generation, while sub-research question four defines the lines in the network with frequencies and the required number of vehicles. This will also give an indication of operational cost. At last, sub-research questions five and six concerns the post result analysis. Questions two, three, four, five and six are in a sequential manner. Answering each of them will help to answer the subsequent one.

1.6 List of assumptions

The list of assumptions used in network design later in this report is presented below. These assumptions are further explained in the subsequent chapters.

1.6.1 Vehicle

- The speed of the vehicles is assumed to be 1000 km/hr for the links >30 km, while for the shorter links, the maximum speed is assumed to be 500km/hr.
- The value of acceleration and deceleration is considered to be 0.5G.
- The capacity of the vehicle is assumed to be 50 sitting passengers per vehicle
- The minimum headway of 90 seconds has been assumed considering the time of passengers moving in-out and time required for fastening their seat belts.

1.6.2 Network & service

- Links are considered to be non-planar i.e. intersecting links do not generate a node.
- The nodes are fixed.
- The demand is assumed to be fixed throughout the design process.
- All the links are considered bi-directional.
- No capacity restrictions are considered while generating the network.
- No overtaking possibilities over the lines are considered. This leads to a line capacity of 2000 passengers per hour per direction.
- The networks are required to be connected.

1.7 Outline

Thus, the research question and bases for the research have been defined. Chapter 2 defines the problem mathematically and describes the methodology with a detailed literature review, whereas chapter 3 is case-specific where inputs for the model have been developed. Chapter 3 answers the sub-questions one as well. Chapter 4 discusses the results and performs the cost-benefit analysis with the case-specific guidelines, and chapter 5 concludes the study by discussing recommendations and limitations. As described here, Figure 1-1 shows the flow of the research along with the chapter number indicated for the thesis.

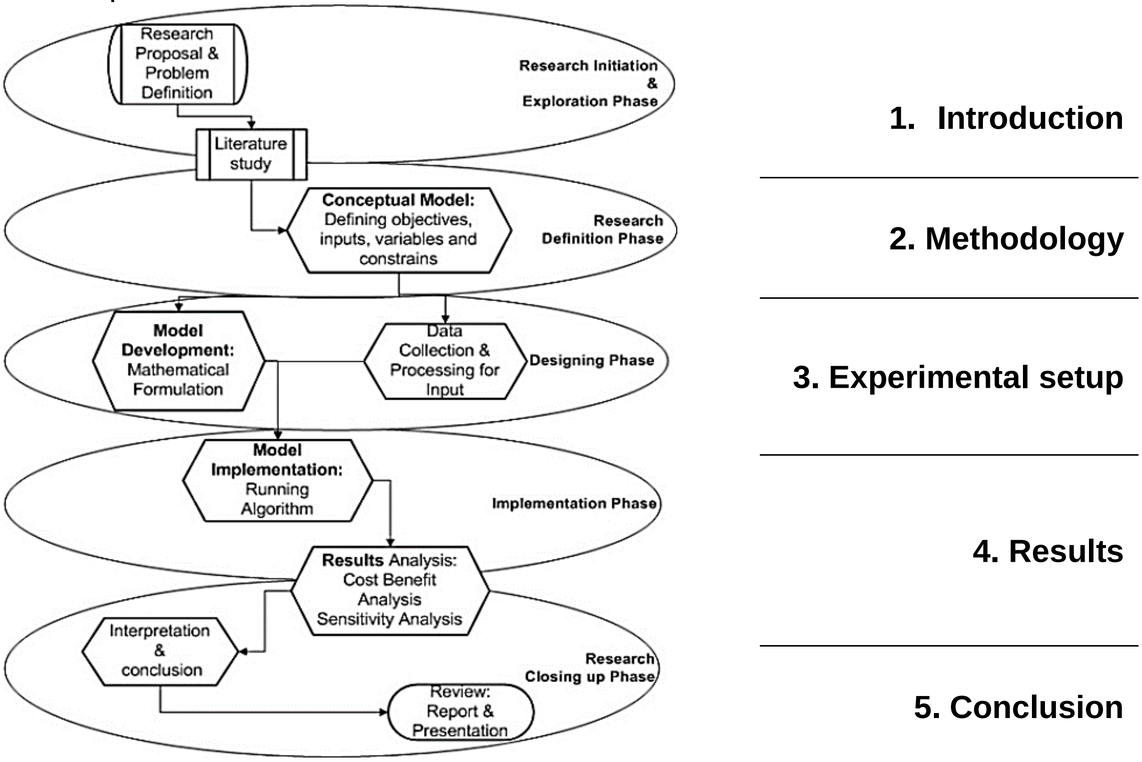


Figure 1-3 Outline of the project

2 Methodology

This chapter describes the study approach developed to answer the main research question. Also, in order to define the approach, it is required to identify the methods that are being practised in the field of network design and optimisation. The chapter starts with section 2.1 describing and reviewing the previously implemented design and optimisation approaches. This helps to answer the sub research question two. Section 2.2 describes the adapted study approach, in all the stages of design i.e. network generation, route design and assignment procedure. This will answer the sub research question two.

2.1 Selecting the modelling approach

As mentioned, this section identifies the methods adopted and helps to formulate the design method for the current design problem through literature review. Transit network design problem (TNDP) has been defined as a complex and difficult to solve problem. It has been studied for more than five decades. The current section captures important studies that have dealt with this topic previously. Kepaptsoglou et al (2009) compiled more than 60 studies in the field of TNDP in a detailed literature review. Farahani et al. (2013) also carried out a literature review extending the works of Kepaptsoglou et al (2009). However, the categorisation of the problems is different in all of the studies. As mentioned in the background section of the document, the problem solution is largely classified into two categories, i.e. Conventional and Heuristic (Baaj & Mahmassani, 1991). This section explains both classifications from the literature.

Conventional methods include analytical approach and mathematical programming (Kepaptsoglou et al., 2009). Farahani et al. (2013) defined them as exact or mathematical methods. Analytical methods identify relationships between the components of transit networks (Ceder et al., 1986; van Oudheusden et al., 1987; Chakroborty, 2003). Generally, these solutions are developed for local optimisation based on mathematical properties (Kepaptsoglou et al., 2009). Earlier applications of these methods can be observed in small networks (Holroyd, 1965; Hurdle, 1973; Byrne, 1976; Byrne, 1975; Kocur & Hendrickson, 1982). As these methods are considered to be inefficient for large networks, they were applied by some of the researchers to medium size networks (Tsao & Schonfeld, 1983; Chang & Schonfeld, 1993; Chang & Schonfeld, 1993a; Spacovic & Schonfeld, 1994). All these applications were mainly on bus route network design problems with the aforementioned objectives in section 1.3. These methods are considered to be simple and easy to implement for generating small networks. Branch and bound method is a good example of it. Ceder (2001) mentioned that analytical methods can be used for the policy evaluation and to estimate the values for design parameters approximately, not for the complete design. The aforementioned Delft Hyperloop Student Team study is based on the analytical approach.

The other approach is to implement mathematical programming, which is based on solving non-linear equations. These methods are considered to be efficient for non-linear problems and can be used for solving large networks, whereas analytical methods are incapable of doing the same (Tom & Mohan, 2003). The first applications of the same were given by van Nes, Hamerslag & Immers (1988) and Baaj & Mahmassani (1991). These were linear models. The first non-linear models were given by Constantin & Florian (1995) and Russo (1998). However, these studies did not consider routes as decision variables. van Oudheusden et al. (1987) gave an important study with the same approach, where routes were considered as a decision variable. However, the study was based on the plant location problem rather than public transit problem. Some researchers have mentioned the disadvantages of these conventional methods for the route generation. However, these remarks were largely based on the generation of bus routes on large road networks. Chakroborty (2003) also drew attention to the fact that mathematical programming is inadequate to represent the problem to a realistic extent. Tom & Mohan (2003) also noted that these methods are useful for theoretical interest only. However, these methods have also been implemented in other networks like Rail Networks or Ferry Design Networks (Bell et. al., 2019).

The other category of the optimisation methods includes Heuristic Methods and Meta-heuristic Methods. These methods generate a candidate set of routes based on some defined criteria, followed by generating either a subset of optimal routes or improving previously generated routes by adding or removing network elements (Farahani et al., 2013). The heuristic methods are problem-specific algorithms while the meta-heuristic algorithms are globally accepted like Genetic Algorithm, Simulated Annealing or Ant/Bee-Colony Algorithm. One of the important and initial works pertaining to this approach was given by Mandl C. E. (1980) for route designing and frequency setting. The algorithm was based on the shortest path between a pair of terminals serving the maximum number of Origin-Destination (OD) pairs. The idea was to have minimum travel time by reducing the waiting time and transfers. These methods are efficient in terms of computational power and can be implemented on large networks effectively (Farahani, et al., 2013). However, methods do not give global optimal solutions but provide one of the nearly optimal solutions fitting into criteria (Kepaptsoglou, et al., 2009). These methods have largely been implemented for the last three decades. They require a thorough understanding of the problem as a decision is in each step. This will also decide the following step. The heuristic methods have been given lesser attention compared to meta-heuristic methods.

As mentioned before, meta-heuristic methods include partly predefined algorithm. In general, all the meta-heuristic algorithms have been implemented in other fields before being implemented in the field of transportation. These methods do not require detail mathematical formulation of the algorithm. Among these methods, the most widely adopted approach is Genetic Algorithm (GA). One of the initial applications of GA in TRNDP was given by Chien S. et al. (2001). The authors optimise bus routes and their headways by minimising the total cost. GAs have hence been used to determine routes, fleet size, and frequency with different objective functions. Being widely adopted GAs, some contradictory observations have been noted by authors in terms of the quality of results. Many researchers have also noted that GAs perform worse than Simulated Annealing (SA) or Ant Colony Optimization (ACO) (Fan & Machemehl, 2006). Since the last decade, another approach known as the Ant Colony Optimization/Bee Colony Optimization has started to be practised in TNDP. One of the initial applications of ACO was given by Hu et al. (2005) in bus transit networks to optimize the routes and headways with the objective of maximising the passenger flow in the network. In a similar way, ACO has been used for route optimization, optimal station locations, headways and frequency with different and multi-objective functions. However, it has been noted that ACO takes longer computational time. There have been also attempts to implement the hybrid meta-heuristic approach. One of the initial studies noted that integrating SA and GA gave better results than GA only (Zhao & Zeng, 2007). Zhao et al. (2007) combined Tabu Search method & SA instead of GA and observed that the results are good in a considerable amount of time. To reduce the computation time for the convergence, Vitins, B. (2014) also combined ACO and GA, as the former had greater accuracy and the latter had shorter computational time. The algorithm was used to optimise the road network in Switzerland in order to minimise the user cost. The author also found that integrated approach outperforms GA, in terms of accuracy.

From the above-mentioned studies and methods for transit network optimization, the characteristics of the methods are summarized as per Table 2-1. The table shows five characteristics of each method starting from complexity, followed by large network suitability, computational time, quality of results, level of detail and type of optimisation. The categorisation of the methods is followed from Kepaptsoglou et al. (2009). The properties are taken up from the literature. This also includes the interpretation of the author, which can be subjective to some extent. The characteristics of complexity, quality of results and level of detail are measured in high, medium and low, while large network suitability yes, medium and no. The optimisation has been distinguished between local and global. From the categories, meta-heuristics found out to be the best except in the quality of results. This is due to less accuracy of GA and ACO.

Table 2-1 Optimisation methods' characteristics

	Method		Complexity	Large Network Suitability	Time for Computation
1	Conventional	Analytical	Low	No	High
2		Mathematical Programming	High	Medium	Medium
3	Heuristic	Heuristic	Medium	Medium	Low
4		Meta-heuristic	Low	Yes	Mixed
	Method		**Quality of Results**	**Level of Detail**	**Optimisation**
1	Conventional	Analytical	High	Less	Local
2		Mathematical Programming	High	Medium	Mixed
3	Heuristic	Heuristic	Medium	High	Global
4		Meta-heuristic	Low	Medium	Global

The above-mentioned studies show single method implementation or hybrid to some extent. Often heuristic methods are merged with mathematical programming in order to solve TNDP. This has been developed through bi-level optimisation in which the upper-level optimisation of route configuration has been carried out with mathematical programming, while lower-level optimisation with meta-heuristic algorithms. Fan & Machemehl (2011) used a genetic algorithm for the bi-level optimisation. The upper-level optimisation was performed with GA in order to develop the transit network with minimum operational cost, while the lower level was based on mathematical programming in order to generate routes and frequency with minimum user cost. Also, in this approach, the studies show sequential and simultaneous approaches for network generation and route design. It has been noted that the latter gives better results in terms of quality.

2.2 Adapted modelling approach

As mentioned in the previous chapter the current network design is carried out in two stages. The first one includes network generation, while the second one route design and frequency setting. In the current section, the main steps of each stage are explained. Figure 2-1 shows the main steps of the overall research methodology.

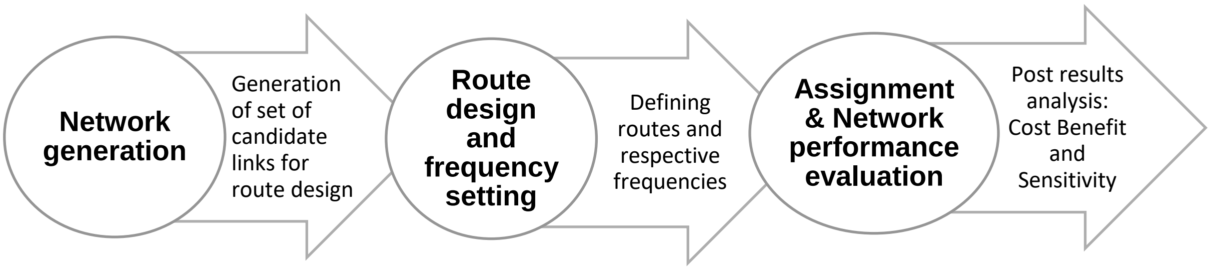


Figure 2-1 Research methodology

Considering the characteristics of Hyperloop, for the network generation heuristic approach can be adopted. This is mainly because of smaller Hyperloop networks. Since higher mode speed and larger distance requirement for acceleration will lead to larger stop spacing. This will lead to a smaller size of the networks. Considering the higher cost for station operation, the network is also required to be connected, as stated in one of the assumptions of the study. This will reduce the user cost of transferring to other modes, which will lead to increased benefits.

As mentioned in the research gap, the current study also aims to evaluate the societal cost and benefits of the system, B/C ratio is considered as a performance indicator of the network generation part, while number of transfers which is part of user cost has been considered as an objective function to be minimised for the route design. However, in transport networks benefits are mainly dominated by user cost i.e. travel time savings compared to other benefits like externalities (environmental emissions, noise, accident cost etc.) and cost are mainly dominated by infrastructure and operational & maintenance cost, those have been only considered for the optimisation. This is explained in detail in the subsections.

2.2.1 Network generation

Beets A.D.J. (2019) adopted MST for the network generation. Demand was not part of the consideration for the network generation. However, this approach does not ensure the maximisation of benefits. The current study also considers the demand for the network generation. This leads to the development of two approaches;

(i) Additive approach, in which the initial network is developed based on MST and further improvements in the links are made based on the travel time savings and cost,

(ii) The deductible approach in which initially fully connected network is generated and links are deleted until tree in the network is reached or B/C reaches less than one.

The algorithms are initially used in ferry network design problem with different objective functions. by Bell et al. (2019). However, apart from objective function, adding-removing criteria and convergence criteria were different in the study. The algorithms were named as Link Swapping algorithm and Link Deletion algorithm. Both of the algorithms are heuristic in nature. The similar nomenclature is followed in the current study as the core idea remained the same.

The idea of network generation algorithm is to identify the links that are feasible i.e. B/C ratio is ≥1. However, it may be possible that this will generate redundant links since the gains from travel times are significantly higher because of the very high speed of the mode. This will add a step after route design for the adjustments i.e. removal of redundant links.

it is also important to note that demand is considered to be fixed throughout the process. Also, for the network generation process, only infrastructure cost for the cost part, while for the benefits it is assumed that no transfer, waiting and stop time will be required.

For both the network generation algorithms, the set of nodes; travel times of existing networks, unit infrastructure cost of links and stations cost; and OD matrix are the inputs required to feed. In the subsections explain both the approaches in detail. Both the algorithms generate a feasible set of links along with the B/C ratio for the network with the considered costs and benefits. The B/C ratio is calculated by taking a ratio of travel time savings {(i.e. existing network total travel time and Hyperloop network travel time)* VoT} / infrastructure cost. The following section explains the main steps of the link swapping algorithm and link deletion algorithm.

The following sub-section explains both the approaches with an example and pseudo-code developed in R syntax.

2.2.1.1 Link swapping approach

The general steps of the algorithm are shown in Figure 2-4. The current section explains the main steps of the link swapping algorithm. The algorithm starts with the minimum cost network and develops the network further towards the direction of increasing benefits. The steps of the algorithm as follow:

1. After feeding the inputs, the algorithm is initiated with the MST (set of links E) based on the cost of the network. In this step further, travel times of each link will be calculated based on the parameters mentioned in the assumption section. Based on this travel time, the flow will be assigned to each link. This will help to calculate the B/C ratio(F) of the network.

Figure 2-2 shows an example of the link swapping approach. Sub-figure (1) develops the network in a way that the overall structure has minimum cost and no cycles in the network.

2. In the first iteration, from the non-chosen links (E'), maximum demand OD pair will be connected via a direct link. This will lead to reassigning the flow and recalculating the B/C ratio (F').

3. If the calculated B/C ratio (F') remains greater than one, further links will be added as per the conditioned mentioned in step 2, until the B/C ratio reduces to less than one.
   In the sub-figure (2), link AD is added provided OD pair AD had the maximum direct demand.

4. If the calculated B/C ratio (F') drops below 1, a minimum flow link will be removed, while making sure that the graph remains connected. This will again lead to re-assigning of flow and recalculation of the B/C ratio.
   The B/C ratio of the network still remains above 1. Therefore, another maximum demand link AC is added. However, after re-assigning the demand in the network the overall B/C ratio of the network drops below 1.

5. Step two, three and four are followed in iteratively, until added link and the removed link are the same in the consecutive iterations.
   This will lead to the removal of the minimum flow link AB.

6. If the added link and removed links are the same in consecutive iterations, the algorithm will be stopped. At this point, the network will be considered as an output along with the B/C ratio.

   For the current example, the B/C ratio goes above one after removal of AB link. This will lead to finding another maximum direct OD pair. This turns out to be AB again and in the next step, AB is also removed. So, this converges the algorithm.

Since the network starts with minimum cost, it will have the highest B/C ratio. This approach is contradictory to the following approach. The algorithm identifies the local optima.
The pseudo code developed for the approach in R syntax is shown here in the box. The pseudo code shows only iterative procedure.

```
# get minimum spanning tree matrix, assign demand, and calculate bca
ini_dist_mst <- minimum.spanning.tree(ini_dist_g)
ini_dist_mst <- assign_demand(ini_dist_mst, nr_node, demand_mat_net_gen)
plot(ini_dist_mst)
bca_table <- matrix (c("0",  "initial_mst", "NA",
                 calculate_simple_graph_bca(ini_dist_mst, vot, ett, infra_cost, stations_cost)),
ncol = 6)
# iterative process starts here
new_dist_g <- ini_dist_mst
new_links <- NULL
iter <- 0
repeat {iter <- iter + 1
  print(iter)
   # add direct link for the link with maximum flow which is not on graph already
  # on the condition that the link adds on the old bca
```

```
    # the function will loop until a link is found
    repeat {new_dist_g <- add_max_demand_link(ini_dist_g, new_dist_g,
    if(!is.null(new_links)) gsub(", ", "|", new_links) else NULL, nr_node, demand_mat_net_gen)
        link_added <- paste(new_dist_g[[2]], collapse = ", ")
        new_links <- c(new_links, paste(new_dist_g[[2]], collapse = ", "))
         bca <- calculate_simple_graph_bca(new_dist_g[[1]], vot, ett, infra_cost, stations_cost)
        bca_table <- rbind(bca_table, c(iter,  "link_added", link_added, bca))
        new_dist_g <- new_dist_g[[1]]
         if(bca[[3]] < 1) break    }
     repeat {
     # remove minimum flow link
     # on the condition that the graph stays connected and bca becomes higher than 1
     # if the conditions are not met then the link will not be removed
     #and link with second minimum will found etc until conditions are met
     new_dist_g <- remove_min_demand_link(new_dist_g,
                                vot, ett, infra_cost, stations_cost,
                                nr_node, demand_mat_net_gen)
     link_removed <- paste(new_dist_g[[2]], collapse = ", ")
     new_dist_g <- new_dist_g[[1]]
     bca <- calculate_simple_graph_bca(new_dist_g, vot, ett, infra_cost, stations_cost)
     bca_table <- rbind(bca_table, c(iter,  "link_removed", link_removed, bca))
     # move to another iteration of adding/removed
     # until the link added is the same as link removed
      if(bca[[3]] > 1) break }
     if(link_added == link_removed) break}
    # plot final graph
plot(new_dist_g)
```

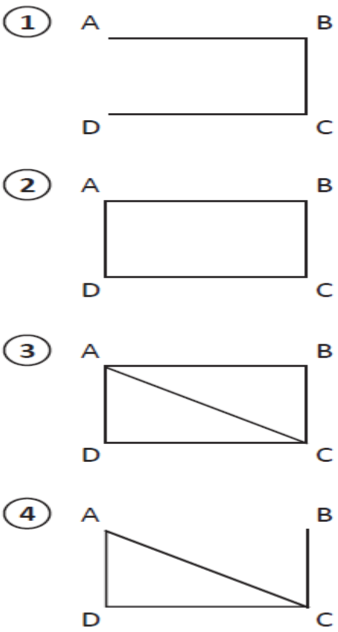


Figure 2-2 An example of link swapping

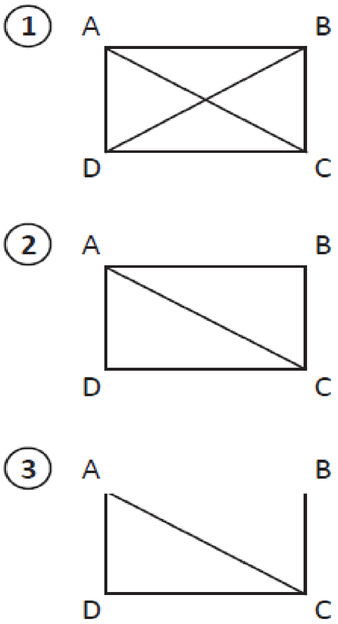


Figure 2-3 An example of link deletion

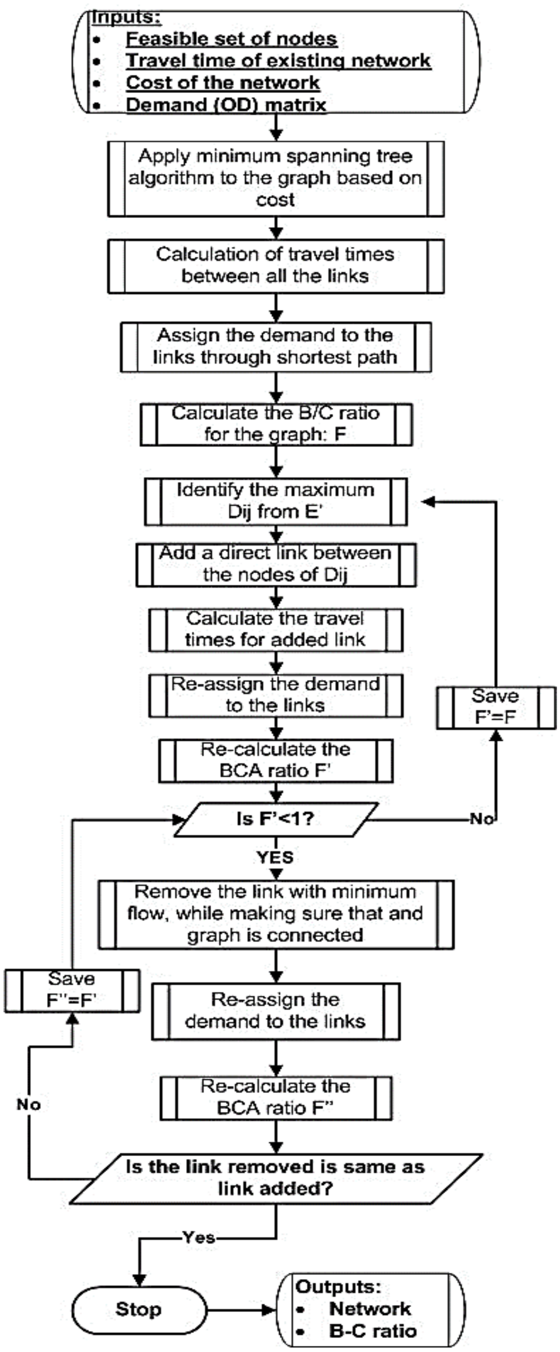


Figure 2-4 Link swapping algorithm

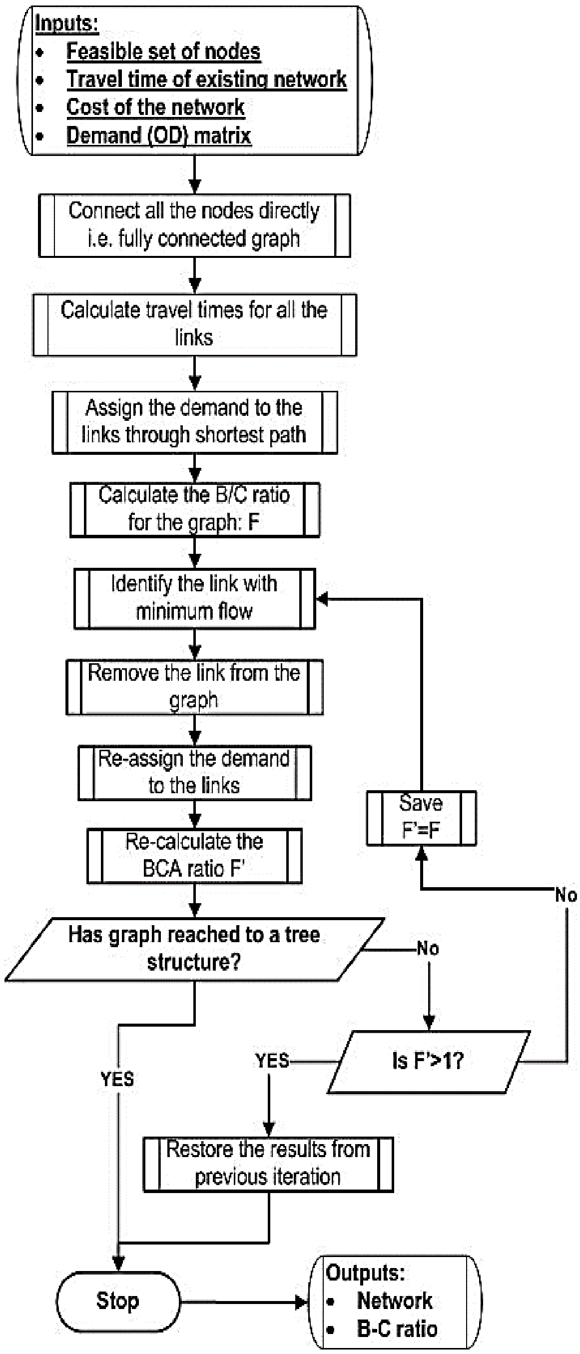


Figure 2-5 Link deletion algorithm

2.2.1.2 Link deletion approach

The general steps of the link deletion algorithm are shown in Figure 2-5. This algorithm starts with the maximum connected network and progresses towards reducing the network. The main steps from the figure are explained below:

1. After feeding the inputs, the algorithm starts with connecting all the nodes to each other. This will generate a fully connected network. Once the network is generated the flow will be assigned to the links via shortest paths and subsequently, B/C ratio will be calculated for the graph based on the travel times calculated according to parameters mentioned in the assumptions.

Figure 2-3 shows an example of the link deletion approach. In the first step, as it can be seen from the sub-figure (1), al the nodes are connected, and demand is directly assigned.

2. In the next step, a minimum flow link will be removed. This will lead to the re-assigning of the flow and re-calculation of the B/C ratio.
   As sub-figure (2) shows in the next step, link BD is removed since the link has minimum demand and B/C ratio is above one.

3. Step two will be followed iteratively until the network reaches the tree structure or the B/C ratio is reduced to less than one.
   As sub-figure (3), shows the link AB is removed since it has minimum demand after re-assigning the demand of the network.

4. If the network reaches to the tree structure, the same iteration results will be stored, and the network will be considered as an output.
   In further, the link AC could be removed. However, this led to reducing the B/C ratio of less than one. Therefore, link AC is restored in the network.

5. If the B/C ratio of the network reaches to one, one iteration previously, results will be stored, and the network structure will be considered as output.

This approach of link deletion tries to identify the global optimum. The algorithm starts with the minimum B/C ratio and progresses towards the improving B/C ratio of the network.
The pseudo code developed for the approach in R syntax is shown here in the box. The pseudo code shows only iterative procedure:

```
# export adjacency matrix of initial graph
write.csv(as.matrix(get.adjacency(ini_dist_g)),   "AdjacencyMatrixFullGraph_m2.csv")
# initial bca table to be exported
bca_table <- matrix(c("0",  "initial_fg", "NA",
                  calculate_simple_graph_bca(ini_dist_g, vot, ett,
                                     infra_cost, stations_cost)), ncol = 6)
# iterative process starts here
new_dist_g <- ini_dist_g
new_links <- NULL
iter <- 0
repeat {  iter <- iter + 1
  print(iter)
  # remove minimum flow link
  # on the condition that the graph stays connected
  # if the conditions are not met then the link will not be removed
  #and link with second minimum will found etc until conditions are met
  new_dist_g <- remove_min_demand_link_m2(new_dist_g,
                              vot, ett, infra_cost, stations_cost,
                              nr_node, demand_mat_net_gen)
  link_removed <- paste(new_dist_g[[2]], collapse = ", ")
  breaks <- new_dist_g[[3]]
  new_dist_g <- new_dist_g[[1]]
  bca <- calculate_simple_graph_bca(new_dist_g, vot, ett, infra_cost, stations_cost)
  bca_table <- rbind(bca_table, c(iter,  breaks, link_removed, bca))
  # break if network gets disconnected or if network becomes a tree
  if(breaks %in% c("stop_removing_tree", "stop_removing_bca")) break}
# plot final graph
plot(new_dist_g)
```

Both of these approaches identify the networks with the feasible set of links i.e. B/C ratio above one. This network will be considered as an input for the next route design algorithm. The following sub-section explains the route design stage.

2.2.2 Network route design and frequency setting

The networks generated in the previous step are taken up for the route design. As mentioned previously, the route design algorithm is based on Mandl C.E. (1980) approach. This is one of the earliest applications of Heuristic methods in TNDP. The algorithm optimises the number of transfers on a set of lines.

As there are two different networks will be generated from the previous stage, the route designing algorithm will be applied to both the networks. Figure 2-6 shows the general steps for the algorithm. The main inputs for the algorithm will be a network with OD demand matrix. The general steps are described below:

1. In the first step, the algorithm identifies the longest shortest path of the network and saves it as a line. Once a line is selected, the selected links and nodes are deleted from the network while ensuring that the rest of the network is connected.
   Figure 2-7 shows an example of the route design[3]. As per the longest shortest paths of the network, BED and AEC are two lines generated from the network.
2. With the same conditions, the second line is identified. This process is followed iteratively until all the nodes are covered at least by a line. Here, while selecting a line, one must make sure that in the same line a node is not visited twice. This avoids cycles in a line.
3. Once a set of lines is defined, the maximum number of transfer point is identified between each pair of lines via assigning the flow on each line.
   This identifies E as the maximum number of transfer point in the given set of lines.
4. In the next step, the number of transfers will be calculated on the transfer node.
5. In this step, the portions of the lines are interchanged from the identified maximum transfer point in the previous step. This process is iteratively followed for all the possibilities.
   This will lead to a generation of a different combination of lines, like AED & BEC and AEB & CED as shown in sub-figure (3) and (4).
6. The set of lines with the minimum number of transfers will be considered as an output of the algorithm.
7. On this set of lines, the load profile is plotted for each line. Based on the maximum load on the line, the frequency of each line will be calculated. This will also help to calculate the number of vehicles required in combination with cycle time.

[3] This example is not in continuation with the previous example.

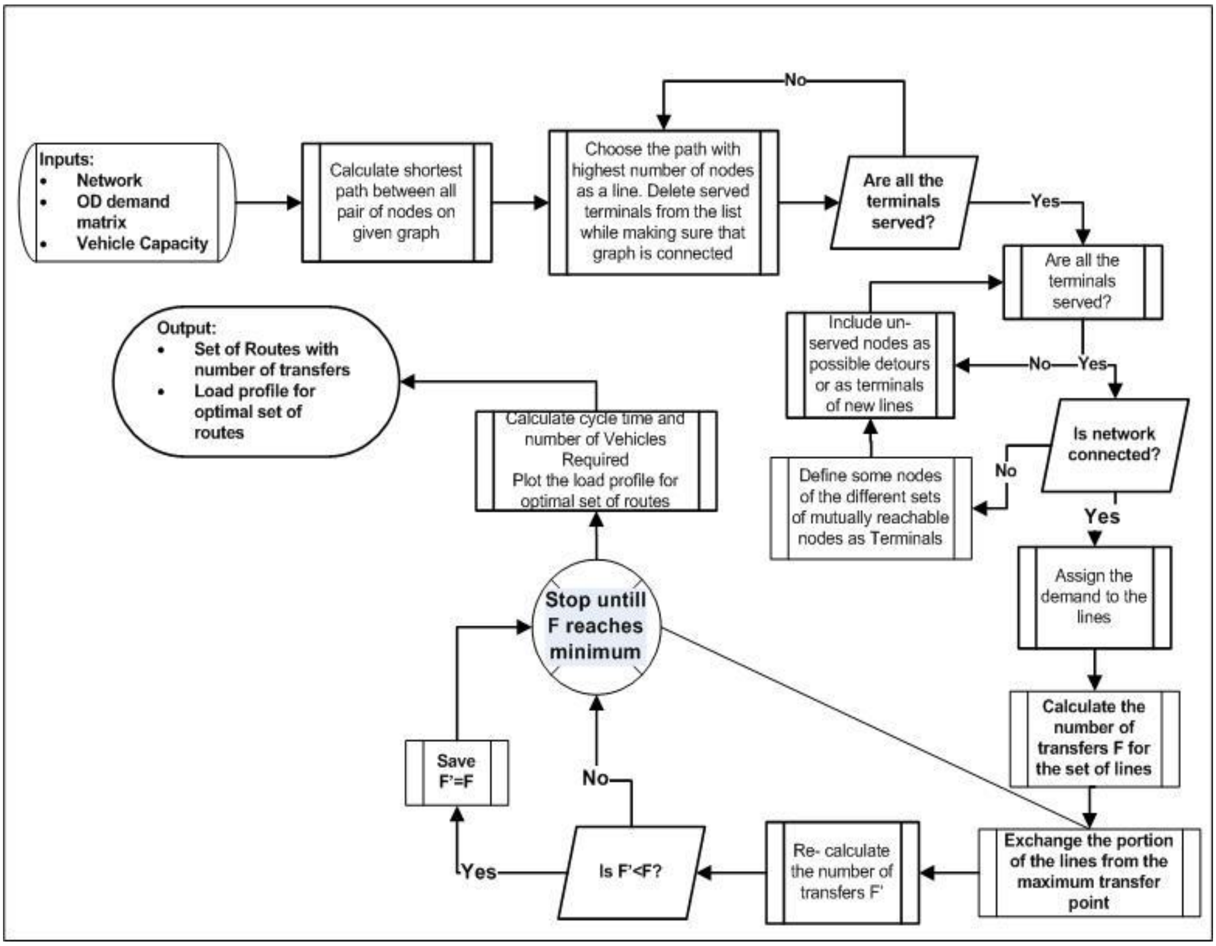


Figure 2-6 Route design algorithm

The algorithm gives routes with assigned frequency (also fleet size) as output. It generates the routes based on the shortest path initially which minimises the operator's cost and proceeds towards reducing user cost by minimising the number of transfers. It is also important to note that the algorithm initially does not consider overlapping routes, which makes heuristic nature of it.

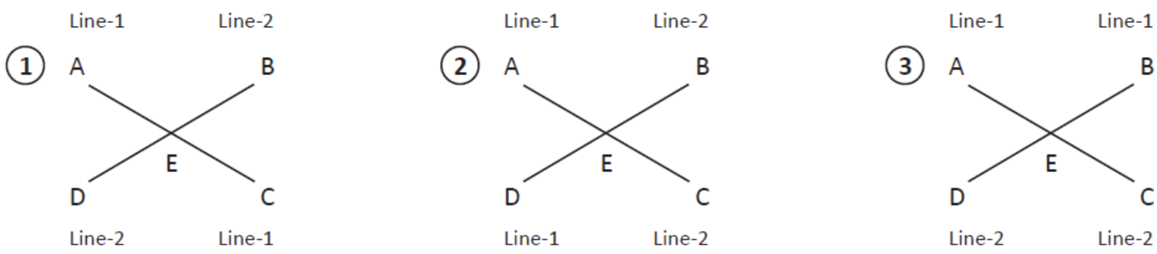


Figure 2-7 An Example of route design

The pseudo-code developed in R syntax for the routes is shown in the box on the next page:

```
get_ids_with_single_edge <- function(graph) {
  ids <- NULL
  all_nodes <- names(unique(V(graph)))
  for(i in all_nodes) {
    if(length(which(as.vector(get.edgelist(graph)) == i)) == 1) ids <- c(ids, i) }
  return(ids)}
# get nodes with maximum transfer points
get_node_with_maximum_transfer <- function(graph) {
  temp <- table(as.vector(ends(graph,E(graph))))
  return(names(which(temp == max(temp))))}
swap_all_lines <- function(line_i, line_j, nodes) {
  interchange_i <- which(line_i %in% line_j & line_i %in% nodes)
  interchange_j <- which(line_j %in% line_i & line_j %in% nodes)
  if(interchange_j[length(interchange_j] == length(line_j) |
     line_i[length(line_i)] == line_j[length(line_j)] |
     !all(line_1[which(line_2 %in% line_1)] == line_2[which(line_2 %in% line_1)])) {
        line_2 <- rev(line_2)
        interchange_2 <- which(line_2 %in% line_1 & line_2 %in% nodes)  }
  line_mod_11 <- c(line_1[1:(interchange_1[length(interchange_1)])],
              line_2[(interchange_2[length(interchange_2)] + 1):length(line_2)])
  line_mod_12 <- c(line_2[1:(interchange_2[length(interchange_2)])],
                line_1[(interchange_1[length(interchange_1)] + 1):length(line_1)])
  if(line_mod_11[1] == line_mod_11[length(line_mod_11)]) line_mod_11 <- line_1
  if(line_mod_12[1] == line_mod_12[length(line_mod_12)]) line_mod_12 <- line_2
  return(list(line_mod_11, line_mod_12))}
# get all the scenarios of lines by swapping ends of common nodes
get_all_lines_scenarios <- function(lines, max_transfer_pts) {
  scenarios <- list(lines)
  for(i in 1:(length(lines) - 1)) {
    for(j in (i+1):length(lines)) {
      lines_mod <- swap_two_lines(lines[[i]], lines[[j]], max_transfer_pts)
      lines[[i]] <- lines_mod[[1]]
      lines[[j]] <- lines_mod[[2]]
      scenarios <- c(scenarios, list(lines)) }  }  return(scenarios)}
# get load profile for lines
get_load_profile <- function(graph, line, demand_matrix) {
  temp <- rep(line, each=2)[-1]
  temp <- temp[-length(temp)]
  line_edges <- get.edge.ids(graph, temp)
  sub_g <- subgraph.edges(graph, line_edges, line_edges)
  sub_demand <- demand_matrix[which(rownames(demand_matrix) %in% names(V(sub_g))),
                          which(colnames(demand_matrix) %in% names(V(sub_g)))]
  sub_g <- assign_demand(sub_g, nrow(sub_demand), sub_demand)
  return(sub_g)}
get_load_profiles <- function(graph, scenarios, demand_matrix) {
  d12 <- data.frame()
  for (i in 1:length(scenarios)) {
    for (j in 1:length(scenarios[[i]])) {
      temp <- get_load_profile(graph, scenarios[[i]][[j]], demand_matrix)
      d12 <- rbind(d12, data.frame(scenario = i, line = j,
                              line_name = paste0(scenarios[[i]][[j]], collapse=","),
                             edge = as_ids(E(temp)), load_profile_dir1 = E(temp)$assigned_demand_d1,
                             load_profile_dir2 = E(temp)$assigned_demand_d2)) }}return(d12)}
# get frequency of each line
get_line_freq <- function(graph, line, demand_matrix, veh_capacity) {
  lp <- get_load_profile(graph, line, demand_matrix)
  d1 <- which.max(E(lp)$assigned_demand_d1)
  d2 <- which.max(E(lp)$assigned_demand_d2)
  m <- which.max(c(E(lp)$assigned_demand_d1[d1],E(lp)$assigned_demand_d2[d2]))
  if(m == 1) {
    return(data.frame(line = paste0(line, collapse = ","),
```

```
                    link_with_max_directional_demand = as_ids(E(lp)[d1]),
                    assigned_demand = E(lp)$assigned_demand_d1[d1],
                    freq = E(lp)$assigned_demand_d1[d1] / veh_capacity))  } else if(m == 2)
{    return(data.frame(line = paste0(line, collapse = ","),
                    link_with_max_directional_demand = as_ids(E(lp)[d2]),
                    assigned_demand = E(lp)$assigned_demand_d2[d2],
                    freq = E(lp)$assigned_demand_d2[d2] / veh_capacity))}}
get_lines_freq <- function(graph, scenarios, demand_matrix, veh_capacity) {
    lines_freq <- data.frame()
  for(i in 1:length(scenarios)) {
    for(j in 1:length(scenarios[[i]])) {
      lines_freq <- rbind(lines_freq, cbind(scenario = i,
                                    get_line_freq(graph, scenarios[[i]][[j]],
                                            demand_matrix, veh_capacity)))}  }  return(lines_freq)}
get_first_line <- function(graph) {
  ids <- get_ids_with_single_edge(graph)
  all_paths <- NULL
  all_weights <- NULL
  for(i in 1:(length(ids)-1)) {
    for(j in (i+1):length(ids)) {
      paths <- all_simple_paths(graph, ids[i], ids[j])
      weights <- NULL
      for(k in 1:length(paths)) {
        path <- paths[[k]]
        temp <- rep(names(path), each=2)[-1]
        temp <- temp[-length(temp)]
        weights <- c(weights, sum(E(graph)$weight[get.edge.ids(graph, temp)]))}
      all_weights <- c(all_weights, weights)
      all_paths <- c(all_paths, paths)    }  }
  all_nr_nodes <- unlist(lapply(all_paths, length))
  first_line <- all_paths[[which(all_weights == max(all_weights[all_nr_nodes ==
max(all_nr_nodes)]))]]
  remaining_nodes <-  names(V(graph)[which(!V(graph) %in% first_line)])
  remaining_single_ids <- remaining_nodes[which(remaining_nodes %in% ids)]
  return(list(first_line, remaining_nodes, remaining_single_ids, overlap = names(first_line)))}
get_other_lines <- function(graph) {
  df <- data.frame()
  first_line <- names(get_first_line(graph)[[1]])
  final_lines <- list(first_line)
  single_ids <- get_ids_with_single_edge(graph)
  remaining_nodes <- get_first_line(graph)[[2]]
  overlap <- get_first_line(graph)[[4]]
  remaining_single_nodes <- get_first_line(graph)[[3]]
  repeat {
    if(length(remaining_single_nodes) > 1) {
      for(i in 1:(length(remaining_single_nodes)-1)) {
        for(j in (i+1):(length(remaining_single_nodes))) {
          path <- shortest_paths(graph, remaining_single_nodes[i],
                              remaining_single_nodes[j], out = "vpath")[[1]][[1]]
          df <- rbind(df, data.frame(n1 = remaining_single_nodes[i], n2 = remaining_single_nodes[j],
                                path_len = length(names(path)),
           overlap_len = length(which(first_line %in% names(path))),
            overlap_remaining_nodes = length(which(names(path) %in% remaining_nodes))),
stringsAsFactors = FALSE) } } } else if (length(remaining_single_nodes) == 1) {
      for(i in single_ids[-which(single_ids == remaining_single_nodes)]){
        path <- shortest_paths(graph, remaining_single_nodes[1],
                            i, out = "vpath")[[1]][[1]]
        df <- rbind(df, data.frame(n1 = remaining_single_nodes[1], n2 = i,
                                path_len = length(names(path)),
                                overlap_len = length(which(first_line %in% names(path))),
  overlap_remaining_nodes = length(which(names(path) %in% remaining_nodes))),
```

```
              stringsAsFactors = FALSE) }    }
    select <- df[which.min(df$overlap_len),]
    select <- select[which.max(select$overlap_remaining_nodes),]
    select <- select[which.max(select$path_len),]
    line <- names(shortest_paths(graph, as.character(select[1,1]),
                          as.character(select[1,2]), out = "vpath")[[1]][[1]])
    overlap <- overlap[which(overlap %in% line)]
    final_lines <- c(final_lines, list(line))
    remaining_nodes <-  names(V(graph)[which(!names(V(graph)) %in% unique(unlist(final_lines)))])
    remaining_single_nodes <- remaining_nodes[which(remaining_nodes %in% single_ids)]
    df <- data.frame()
    if(length(remaining_nodes) == 0) break  }
  return(final_lines)}
```

2.2.3 Assignment procedure

Once the routes and frequencies are identified, the assignment of the Hyperloop network will be performed with the existing networks to evaluate the performance through Cost-Benefit Analysis (CBA). The purpose of performing along the existing network is to capture the larger network-wide effects. However, before performing the assignment, if there are redundant links are found in the network post route design phase, they need to be removed. The case-specific assignment model will be explained in Chapter 3.

3 Experimental set-up: the Swiss case

After determining the method for the network design, the current chapter identifies the inputs for the model. This chapter answers the sub-research question one. The study is performed in the case of Switzerland. As described in the related work (Section1.2), the case of Swissmetro could not be realized due to the higher cost of infrastructure. In this context, Hyperloop is suitable since the infrastructure cost is reduced comparatively. This is because it allows the elevated structure as well. The section explains the case along with the preparation of inputs in sections 0. Before developing the inputs, the chapter defines the scenarios in section 3.1.

3.1 Scenario design

The current section of the document explains the scenario developed for the analysis. As described in the methodology section, there are two methods for network generation. This can generate two different solutions.

The Swiss government provides annual or monthly subscriptions to users of public transport. These subscriptions are known as GA (general abonnement)[4] and HTA (Half fare travel card)[5]. The former one allows a passenger to access free public transport nationwide (SBB, 2019), while the latter one allows all the tickers with half prices (SBB, 2019). From the structural census data of 2010, it is observed that 5% of the population in Switzerland holds the subscription of GA, while 28.97% of the population holds subscription of HTA. However, the share of PT in 2010 peak hour is also 33.5% (ARE, 2016). This leads to understanding that a larger share of PT travellers owns one of the subscriptions. These subscriptions are also increasing in two folds every year since 2010 (The Swiss Broadcasting Corporation, 2019). It is also important to mention that all the public transport service within Switzerland are obliged to operate under the subscription of GA. However, considering the higher infrastructure cost, dedicated infrastructure for Hyperloop and significantly higher speed than any other mode of transport, the Hyperloop system also justifies a separate fare system. In that case, it will be interesting to compare the networks and B/C ratio of both the scenario i.e. without fare pricing (within GA/HTA subscriptions) and with a separate fare pricing of the Hyperloop Network. This will lead turn into the development of four scenarios (cases). Table 3-1 shows this relation namely.

Table 3-1 Scenario development

	Without fare: demand	**With fare: demand**
Link Swapping Method	*Scenario 1.1*	*Scenario 1.2*
Link Deletion Method	*Scenario 2.1*	*Scenario 2.2*

After developing the scenario, the following subsection explains the input preparation along with the case study background.

[4] https://www.sbb.ch/en/travelcards-and-tickets/railpasses/ga.html
[5] https://www.sbb.ch/en/travelcards-and-tickets/railpasses/half-fare-travelcard.html

3.2 Inputs for the model

The current section explains the input developed for the case along introducing the case study. As mentioned in the methodology, mainly three types of inputs are required. This includes stations, costs, demand and existing travel times. The section describes the procedure for the development of each of the inputs.

3.2.1 Stations (nodes)

For the network design the nodes i.e., stations are selected based on the population of the cities within Switzerland. It is assumed that the Hyperloop stations will be mounted on the existing railway stations. The cities with more than 100,000 population in the year 2017 are considered as the main network design stations. This includes the population of the agglomeration as well. Below the list of the cities is mentioned with the longitudes and latitudes of the main stations in decimals. Figure 3-1 shows the location of these stations on the map.

i. Zurich (8.5403, 47.3778)
ii. Genève (6.1425, 46.2103)
iii. Bern (7.4394, 46.9497)
iv. Basel (7.5897, 47.5475)
v. Winterthur (8.7233, 47.5)
vi. Lausanne (6.6292, 46.5164)
vii. Lucerne (8.3106, 47.0489)
viii. St. Gallen (9.3692, 47.4231)
ix. Zug (8.5156, 47.1742)
x. Baden–Brugg (8.3078, 47.4767)
xi. Fribourg (7.1511, 46.8028)
xii. Biel/Bienne (7.2436, 47.1322)

Figure 3-1 Map of the Hyperloop stations

This list also includes the city of Lugano. The city is located in the south across the Alps. However, due to the difficult terrain to construct and is the only city in the south, Lugano is not considered for the network design.

After selecting the stations for the network, the following section explains, the estimation of the cost.

3.2.2 Costs

The total cost can be divided into three aspects i.e. infrastructure cost, operational cost and user cost. Another way to categories these costs is Fixed Cost and Variable Cost. The infrastructure cost is the fixed cost, while the operational cost and user cost are variable costs. The current section derives the costs for the Hyperloop system in terms of fixed and variable cost.

A few studies have been published so far that provide estimates with the cost for the Hyperloop System. The estimates in this section have been made through literature review and; discussions with Swissloop student team[6] and EuroTube[7]. The estimates in Swiss Francs (CHF) have been converted as per the purchasing power parity OECD data (Organisation for Economic Co-operation and Development, 2019) first and then inflation of 1%[8] per year has been applied to estimate the value in the 2040 year.

3.2.2.1 Fixed cost

The section derives the initial investment for the infrastructure. From the understanding of the overall system, the infrastructure cost has been divided into the following elements:

I. Elevated corridor
II. Underground corridor
III. Station cost including Vacuum pumps
IV. Propulsion system
V. Solar panels
VI. Vehicles

The very first cost estimates were published in previously mentioned Hyperloop Alpha (2013) itself (SpaceX, 2013). Though the costs were quite underestimated (Taylor, Hyde, & Barr, June 2016), many of the studies considered it, as the base for the further estimations and discussions (Jeker, 2019) (Covell, 2017). Another estimate was made in “Performances of the HL (Hyperloop) Transport System” by van Goeverden et al. (2017). The study developed key performance indicators for Hyperloop, air transport and high-speed rail; based on costs. The cost estimation in the study was made by comparing the previously published estimate of “Hyperloop Alpha” and a maglev system in China.

Beets (2018) carried out the feasibility of Hardt Hyperloop System between Paris and Berlin. The study forecasted the demand and optimized for the route and frequency between the cities. However, the cost assumptions in the study have not been explained explicitly. Another published preliminary design of Transport system elaborates the cost estimate of the elevated corridor (TransPod Inc., 2017). “The

[6] Swissloop student team is a team of 21 students of diverse background from Switzerland participating in the Hyperloop Alpha Space X competition every year.(https://swissloop.ch/)
[7] EuroTube is a non-profit Research Organization, Building Test infrastructure for sustainable vacuum Transportation. (https://eurotube.org/)
[8] https://www.bfs.admin.ch/bfs/en/home/statistics/prices.html; The assumption of 1% is kept on the higher side to avoid the consequence of cost underestimation.

Future of Hyperloop" by Delft Hyperloop analyzed all the technical aspects of the Hyperloop system and estimates the cost of building system (van Leeuwen, et al., 2019). The report was submitted to the Dutch Ministry of Infrastructure and Water Management in June 2019. Table 3-2 summarizes the estimates in the mentioned studies. In the following paragraph, the comparison is explained in detail as per the list of the elements above mentioned.

I. **Elevated Corridor**: The elevated corridor has two parts to consider i.e. foundation (pylons) and tube. The pylon structures are to be assumed of concrete while the tubes are of steel.

   In the case of the pylons, largely the cost will be proportional to their number/ spacing. The "Hyperloop Alpha" study assumed spacing of 30m, while Transpod assumed spacing of 25 m. Apart from higher spacing in Hyperloop Alpha study, some of the elements were also missed out in the estimation (Taylor, Hyde, & Barr, June 2016). These elements include emergency exits; service roads; Galvanized metal ladder & cage for the maintenance & protection; and galvanized catwalk. These elements have been specified in the preliminary design on the Transpod system with basic dimensions and cost. This led to higher cost estimation in the study, which seems more realistic. The same is considered for the current research.

   The cost of the tube per km mainly depends on its diameter and material. Most of the studies considered steel as a material. However, different assumptions on diameter were noticed. The Hyperloop Alpha considered 3m diameter for the tube, while Hardt System considered 5m diameter. Though the increase in diameter is less than double fold, increase in cost was found to be more than 400% per km. The detailed estimates of Transpod covered the missed-out elements of Hyperloop Alpha study with basic dimensions and cost estimate. Saddle support, bracings, tracks and electrical & mechanical component on 25 m sections of 4 m diameter tubes. 4m diameter is more realistic for the vehicles of 3m ht and 60 pax capacity[9].

   The study of Delft Hyperloop estimates the cost of pylons 0.36 million CHF per km and 21.82 million CHF per km for the tube. The 3.55 m of diameter for the tube and 30 m of spacing has been considered in the study, which is not a significant difference from the other studies. However, Substantial difference has been noticed in the cost estimates of both elements. If the cost of pylons and tube are summed, the estimates are similar to the Transpod estimates.

   The study "Design and Production of Concrete Tubes for Vacuum Transportation Infrastructure" by Heller (2019) compares the cost and performance of tubes made of Steel, Concrete and Polymer Composite Liner. In all of the compared aspects, Polymer Composite Liner performs the best. However, the design assumptions were made on 2.2 m exterior diameter, which makes difficult to incorporate in the current study. Also, the cost difference

[9] Assumption of euro tube and Swissloop as well.

between the Transpod design and polymer composite liner is also not significant.

II. **Tunnel:** The major driving factors for tunnelling cost are geology and diameter. van Goeverden et al. (2017) compared the cost of the tunnelling between Musk's estimate and a few road and rail tunnels around the world. The cost was increased by factor 2.5 from Musk's estimates.

The tunnelling cost in the Delft Hyperloop study is based on the British Tunneling Society cost constants. Those constants have been verified in the study by applying for 21 European tunnelling projects.

For the current research, estimates of van Goeverden et al. (2017) seems quite overestimated. However, considering the geography of Switzerland, the estimates of Delft Hyperloop also needs further detailed investigation.

III. **Stations & Pumps:** The cost of the stations, in Hyperloop Alpha estimates, also Include the cost of vacuum pumps. Hyperloop Alpha (2013) considered a single route, which means two tracks at a station only. This estimation will increase if there are more tracks at a station. van Goeverden et al. (2017) compared this cost of stations with the cost of a maglev station in china. The study also considered the higher assumption of Hyperloop Alpha justifying by the requirement of modern vacuum leakage proof stations. The difference in the estimates of van Goeverden et al. (2017) and Hyperloop Alpha is due to using direct exchange rate conversion between USD and EUR. The Hardt System derived the station cost per km which is difficult to translate in current research. The current research also considers the cost assumption form Hyperloop Alpha. However, the vacuum cost has been considered separately as well. The Delft Hyperloop derived the cost of the station by a case of Delft regional rail infrastructure project. This cost estimate includes 12 Hyperloop platforms. Also, the estimate was made on the basis of the cost of the Berlin Railway station, which faced cost overruns during construction. This turns into the almost six-fold cost of a station in Delft Hyperloop case compared to Musk's estimates.

The vacuum pumps are kept maintain the vacuum air pressure in the tube. The designed air pressure is 1%. Hyperloop alpha estimated combine it with station estimation as mentioned previously. The Swissloop design suggests having vacuum pumps along the corridor similar to Transpod estimations. This leads to the consideration of Transpod estimates. The cost of installation, ventilation and housing was assumed to be by factor four of the capital cost of a ventilation pump in Delft Hyperloop estimates. This led to higher cost estimation.

IV. **Solar Panels:** The solar panels cost was underestimated in the Hyperloop Alpha estimation as it missed out the structural elements and electrification. The same was observed in the Hardt estimation. Delft Hyperloop covered the electrical wiring but missed out structural supports for the plates. This was explained in detail in Transpod estimates, which is considered in the current research as well.

V. **Propulsion System:** The propulsion system has a wide range of assumptions in all the estimates. Delft Hyperloop estimates the propulsion system cost via a case of maglev system and also added the cost of guidance throughout the corridor, this led to overestimates. The Hyperloop Alpha considered linear induction motors for the propulsion, while the Hardt system considers linear synchronous motors similar to Virgin Hyperloop One. The propulsion system can be large of two types i.e. onboard and off-board. After Hyperloop Alpha, most of the systems use off-board propulsion systems. The Swissloop system also assumes to have an off-board propulsion system. However, they also have on-board one to maintain the speed and for the emergencies. Onboard systems make vehicles heavier and are also not capable of accelerating which will be largely covered by off-board part. The cost of the propulsion system is considered as per the Transpod System as the other elements are also more relevant to current research.

VI. **Vehicle Cost:** The Hyperloop Alpha derived 1.35 million USD cost for a capsule with 28 passengers in 2012, while Hardt system derives 3 million euro per capsule for 60 passengers. van Goeverden et al. (2017) takes the reference of a maglev system with 15 million euro per train of 90 passengers' capacity. The same has been considered in case of Delft Hyperloop estimates. The Swissloop capacity and pod sizing assumptions are similar to Hardt System. This leads to the similar assumptions of Hardt System.

Table 3-2 Fixed cost comparison

No	Elements	Costs (Million CHF)					
	Infrastructure cost	Hyperloop Alpha	van Goeverden et al.	Hardt	Transpod	Delft Hyperloop	Current Research
1.	Elevated Corridor (per km)						
	Foundation (Pylons)	8.23	53.73[10]	4.15	9.39	0.36	9.39
	Tube	2.10		8.83	13.35	22.99	13.35
2.	Underground Cost (per km)						
	Tunnel Cost	45.19	125.36[10]	4.87	-	63.41	63.41
3.	Station Cost (per nos.)	239.53	207.75	7.21[11]	-	1261.77	239.53
	Vacuum Pumps (per km)				0.17	0.29	0.17
4.	Solar Panels (per km)	0.69	-	0.39	2.79	1.45	2.79
5.	Propulsion System (per km)	0.36	-	6.49	0.47	23.25	0.47
6	Vehicles (per seat)	0.09	0.30	0.09	-	0.30	0.09

The cost of the land and planning & design is considered 25% of the initial infrastructure cost of the corridor part and 40% of the initial infrastructure cost for the stations. The assumption is made higher in the station since it will require a large

[10] With propulsion system and solar panels and foundations in elevated part
[11] Per km

amount of space in the city and design is also difficult comparatively. However, these both the assumptions are arbitrary. Any of the literature do not introduce these costs for the Hyperloop case, therefore these assumptions need to be made.

The following section describes the maintenance cost and operational cost.

3.2.2.2 Variable costs

As mentioned previously, the variable cost has mainly two parts i.e. maintenance cost & operational cost and user cost. Table 3-3 shows the estimates for the maintenance and operational costs yearly.

The maintenance cost has been assumed by the fixed ratio of the annual investment cost. This ratio of 10% has been considered from the assumption of van Goeverden et al. (2017). The World Bank (2011) stated that variable cost can vary from a few percentages to 30% for rail infrastructure. This was considered as justification for the value in van Geoverden et al. (2017). Further, it was added that no physical contact between vehicles and tracks would require lesser maintenance. Swissloop team also suggests that the vacuumed pressure infrastructure would require less maintenance. The same 10% of average annual capital costs of track, station and vehicles have been considered for maintenance.

The operational cost has mainly two parts i.e. energy cost and labour cost. The Hyperloop Alpha claims to cover all the energy by solar power. However, this does not seem realistic for the Swissloop team. Building solar panels throughout the tube will lead to higher losses and higher maintenance cost. For the current research, it is assumed that the energy for the station will be managed by solar panels laid throughout the tube, while for the operations of the vehicles and tubes energy will be required. Though the Hardt System gave an indication of yearly energy cost, no explanation was given. Besler (2018) carried out energy estimates for the Hyperloop system and compared with a typical railway, maglev and air passenger services.

The assumptions of Besler (2018) varies from the current design considerations. The route of 514 km between Berlin and Munich with a maximum speed of 400 km/hr is the assumption that needs modification in current research. The study categorized energy demand into four parts i.e. levitation energy, magnetic energy, acceleration energy and air drag energy (Besler, 2018). In the current scenario, two parameters will be changing mainly, which is energy due to vacuum loss and air drag energy for higher speed. With the higher length of routes, the leakage increases. However, in the current scenario, the stations will be closely spaced, and leakage will be less as the vacuum pumps will be placed closer. The other energy is air drag, which is largely affected by the speed of the pod. The energy requirement derived in the study is 1 kWh per 100 pass-km at a speed of 400 km/hr. For simplification, it can be increased by 2.5 times (current speed consideration 1000 km/hr). Assuming a Swiss working tariff of 0.30[12] CHF per kWh. The cost of the energy would be 1.15 CHF (2040 rates) per 100 seat-km. This leads to a higher assumption of energy consumption. However, due to unavailability of data, this is considered as the base.

[12] Federal Electricity Commission ElCom: https://www.elcom.admin.ch/elcom/en/home/topics/electricity-tariffs.html

For the manpower, one employee per vehicle is assumed. For stations, four employees are assumed, considering one for each including tickets, information and guiding at platforms; remaining area and traffic management. Considering Swiss labour laws 8 hours a day. 18 hours of public transport operations will make yearly 210,240 hours per station including traffic management. And 52,560 hours per vehicle. Considering 70.30CHF hourly minimum wage (Association Suisse des Professionnels, 2009)[13]. Total cost would be 14,779,872 CHF per station per year and 3,695,082CHF per vehicle per year.

Table 3-3 Maintenance and operational cost

No.	Element	Life Span (Years)	Average Annual Cost (CHF)	Maintenance Cost (CHF)
Maintenance Cost				
1.	Tube	75	530,600	53,060
2.	Tunnel	50	400,500	40,050
3.	Station (per nos)	50	7,185,900	718,590
4.	Propulsion	20	28,200	2,820
5.	Vacuum Pump	20	10,200	1,020
6	Vehicle (per seat)	20	5,400	540
Operational Cost				
6.	Staff Cost	Station	14,779,900	
		Vehicle	3,695,000	
7.	Energy Cost (per 100 seat-km)		1.15	

3.2.2.3 User cost

User cost considers travel time components and fare in the current research. The Value of Time (VoT) is considered from the beta parameters of Swiss National Passenger Transport Model. The values of travel time components are converted into 2040-year values with a given inflation rate of 1%. The overall user time cost has five components which are listed below with their respective values (ARE, 2014). These values are calculated by taking the ratio of the beta parameter of the respective element and the beta parameter of cost. For the network design phase only travel time values are required.

I. Car travel time=28.81 CHF/hr
II. PT: access time= 28.39 CHF/hr
III. PT: transfer time= 4.81 CHF/hr
IV. PT: no. of transfers= 3.25 CHF per transfer
V. PT: in-vehicle time=14.09 CHF/hr

The other part of the user cost is fare. The fare is assumed to be 0.50 CHF/km (2040 rates). This assumption is based on “Study on the prices and quality of rail passenger Services” by the European Commission. The study derives the cost for High-Speed Rail cost in Switzerland 0.27 ch/km in the year 2016, while the 0.33 ch/km for air travel from Switzerland (Steer Davies Gleave, 2016). These values are averaged for 2010, which resulted in 0.27 ch/km.

After the estimation of the costs, the following section explains the demand estimation.

[13] The labor wages of trains have been considered here with 0.75% increase per year.

3.2.3 Demand estimation

The current section of the document explains the demand estimation for the Hyperloop Network in Switzerland from Swiss national passenger transport model (NPVM). To explain the demand estimation, explanation of the working of NPVM and relevant adaptions for the Hyperloop system have been described in this section. The section describes NPVM, followed by assumptions made for demand estimation and at the end Hyperloop demand is estimated.

The following section 3.2.3.1 explains how NPVM was developed. The model explanation is described in the 'Erstellung des Nationalen Personenverkehrsmodells fur den offentlichen und privaten Verkehr (Modellbeschreibung)' and 'Nationales Personenverkehrsmodell des UVEK (Aktualisierung auf den Basiszustand 2010) Endbericht'[14]. It is also important to mention that the documents are available in French, Italian and German. For the current description, it has been translated into English. In this section, no contribution from the author side has been given. The purpose of the section to elaborate on the background of demand estimation.

3.2.3.1 Model explanation

Initially, NPVM was developed in the year 2006, based on the data of the year 2000. After which, an update was made in the model with the data of 2010. The typical four-stage transport model starts with trip generation followed by trip distribution, modal split and the assignment at last. However, NPVM is a three-stage model, in which destination choice and mode choice are carried out simultaneously. To develop the model, the data from various sources were collected. The major sources include 2001 micro census data, commuting data of national railway carrier of Switzerland SBB and stated preference surveys (ARE, 2006). For the modal estimation statistical software Biogeme version, 07 was used, while the assignment procedure was performed in transport and planning software PTV Visum 13.8 separately for the private transport and public transport (ARE, 2006). The following subsection of the document explains the working of the model. The first sub-section explains the structure of the supply network followed by general model development procedure, trip generation and distribution and estimation of mode choice and destination choice parameters at last.

3.2.3.1.1 Zoning and network characteristics

The section describes transport network characteristics and the zoning of the overall network.

The Swiss administrative boundaries at the city level (municipality) were considered as zone boundaries in the network. The big cities namely Basel, Bern, Biel, Geneva, Lausanne, Lucerne, St. Gallen, Thun, Winterthur and Zurich; were further divided at the urban district level zones. Addition to that five largest airports of Switzerland were added as the separate zones. These include Zurich Airport, Geneva Airport, Basel Euro Airport, Bern-Belpmoos and Lugano-Agno. This leads to a total of 3,114 Origin and Destination pairs including outside Switzerland zones (ARE, 2006).

[14] https://www.are.admin.ch/are/de/home/verkehr-und-infrastruktur/grundlagen-und-daten/verkehrsmodellierung/nationales-personenverkehrsmodell.html

The road network was mapped using GIS software as per the state in late 2000. The road network consists of 24,311 nodes, 31,276 roads (60,552 directed edges) and 3,884 connections. These nodes include within Switzerland, European countries and future planned routes as well. This led to a total network length of 23,962.33 km of roads within Switzerland and 112,412.18 km within European countries (ARE, 2006).

The network of public transport consists of 26,780 nodes; 17,689 stops; 15,363 served stops; 30,530 routes (including 3,222 footpaths & 71,060 directed edges); 3,905 connections and 11, 748 sublines. These include modes like trams (inter-zonal), bus lines (inter-zonal), trains, ferry, cable car and walking & biking for access and egress (ARE, 2006).

3.2.3.1.2 Model development

Generating origin-destination matrix, trip purpose-specific can give a better understanding of travel behaviour than a generic one. The model estimated the demand based on trip purpose. Same as the typical four-stage transport model, NPVM also calculated trip generation as a first step. The trip purposes were categorized into five i.e. (i) job; (ii) education; (iii) service; (iv) shopping; (v) leisure, travel and other. (ARE, 2016)

As mentioned previously, the model used a simultaneous approach of destination and mode choice model. The survey results with structural data of zones and estimates of the generalized costs of the routes (travel time, travel costs, frequency of transfers, etc.) were used to estimate the beta parameters of mode and destination choice. These generalized costs were calculated using the network models created for road and public transport. The estimated parameters were used as input to calculate the demand for modes and each zone (ARE, 2006).

3.2.3.1.3 Trip generation and distribution

The productions and attractions of a zone were calculated based on the size of a zone, structural variables (e.g. inhabitants, employment, etc.), socio-demographic characteristics (e.g. age, car ownership, public transport subscriptions etc.) and accessibility. From the parameters derived from these variables, trip generations were calculated based on the EVA model by Lohse (Schnabel and Lohse, 1997) in software VISEVA. The trip generation mainly generated three types of trips i.e. (i) home-based origin (ii) home-based destination (iii) non-home-based trips. With the trip purposes, this will lead to 17 categorises of trips. The overall average for Switzerland based on activity resulted in a total of 3.91 trips per resident per day. (ARE, 2006)

3.2.3.1.4 Destination and mode choice parameters

Once the demand for the activity-based group has been estimated, in the next step parameters for simultaneous destination and mode choice model were estimated.

In order to estimate the modal share, the model was developed using a nested logit model. On the upper level, three nests were considered i.e. MIV (motorized transport), OEV (public transport) and LIV (active modes); while on the lower level along with the mode destination choice were made. This lower level has 11 destination choice. This resulted in 33 destination-vehicle combinations.

To calculate the choice, a three-level utility function was created with sociodemographic, mode-specific and destination characteristics. The factors are listed below as per the respective category:

- **Socio-demographic**: Car availability, an annual subscription of public transport (GA), half-price subscription (HT), age, behavioural differences based on language;
- **Mode specific**: PT travel time, PT cost, Parking search time, Parking cost, PT access time, Car travel time, Car cost, number of transfers, Transfer wait time, walking time for LIV, the difference in height for LIV;
- **Destination choice**: Population, employment, jobs, education facilities, cultural activities/ recreational and parks, parking facilities, retail space, Bern city as the capital

The socio-demographic variables include the availability of car and availability of annual public transport subscription GA and Half price HTA. These variables are calculated at zonal level via deriving the ratio of respective subscriptions (or vehicles) and population of the zone. The age variable considered the average age of the zone. This average age was calculated by taking a weighted average of five different classes of age groups (between 18 to 80 years). Language constants were added based on the domination of French or Italian speaking population. These are added on the origin side. All of the mode choice variables were generated from Visum networks. These variables include car travel time, car cost (product of unit cost and car distance), PT travel time, PT number of transfers, PT waiting time, PT access time, PT cost (product of unit cost and PT distance). The travel cost 0.16 CHF/km and 0.20 CHF/km were considered for car and public transport respectively. Parking search time and parking cost are varied as per the location and according to the activity duration. The destination choice variables considered the characteristics of origin as well as destination side. They were calculated based on the following equation. The equation explains for the working (commuting) population.

$$Destination\ choice\ vector = \\ ((Orgin\ side\ employed\ people\ vector\ X\ Destination\ side\ available\ jobs\ vector\ ))/ \\ ((Orgin\ side\ employed\ people\ vector +\ Destination\ side\ available\ jobs\ vector)/2)\ )$$

Here, the vector is the product of the beta parameter and variable value. The values of the parameters have been shown in Table 3-4. The parameters were estimated for different trip purposes. The Bern capital constant is added for the OD pairs with origin or destination as ‘Bern’ city and with a population more than 7,500 as per NPVM.

The utility function was formulated separately for each of the trip purposes. The following groups of the population have been considered for each of the trip purposes.

- Work: employment, jobs available
- Education: population, institutes
- Service: employment, jobs available
- Shopping: population, retail space,
- Leisure& other: recreational spaces, population

The utility function has been formulated as below:

$$V_{ijk} = \boldsymbol{Constant} + \sum_{i} \beta_{mode\ related\ i} * X_{mode\ related\ i} + \sum_{j} \beta_{destination\ related\ j} * X_{destination\ related\ j} + \sum_{k} \beta_{socio-demographic\ k} * X_{socio-demographic\ k}$$

Where i is origin zone, j is destination zone and k is transport mode.

Table 3-4 Modal parameters (ARE, 2016)

Parameters		**Work**	**Education**	**Service**	**Shopping**	**Leisure and Others**	**Total**
Morning Peak Hour	Car (%)	*61.70*	*03.70*	*05.40*	*17.30*	*11.90*	100
	PT(%)	*49.50*	*28.50*	*01.80*	*07.00*	*13.20*	100
Daily(%)		*25.30*	*08.70*	*09.00*	*24.20*	*32.80*	100
Car (PW)/(MIV)							
Travel Time [min]		-0.0490	-0.0610	-0.0310	-0.0530	-0.0210	-0.0402
MIV-Availability		1.1180	1.1180	1.1530	1.2570	0.7150	1.0226
Travel Cost [CHF]		-0.1910	-0.3140	-0.0250	-0.1260	-0.0490	-0.1245
Parking Time [min]		-0.0520	-0.0650	-0.0330	-0.0560	-0.0220	-0.0425
Parking Cost [CHF]		-0.2550	-0.4210	-0.0340	-0.1700	-0.0660	-0.1670
Language French		0.2250	0.2250	0.2250	0.2250	0.2250	0.2250
Language Italian		0.3700	0.3700	0.3700	0.3700	0.3700	0.3700
Capital Bern		2.5000	0.0000	2.5000	0.0000	0.0000	0.8575
Mode Specific Constant		3.5000	3.5000	3.5000	3.5000	3.5000	3.5000
Public Transport (PT)(OV)							
Travel Time [min]		-0.0280	-0.0320	-0.0230	-0.0330	-0.0140	-0.0245
Access Time [min]		-0.0560	-0.0560	-0.0340	-0.0750	-0.0330	-0.0511
Travel Cost [CHF]		-0.1910	-0.3140	-0.0250	-0.1260	-0.0490	-0.1245
Transfer Wait Time [min]		-0.0140	-0.0140	-0.0100	-0.0060	-0.0050	-0.0088
No. of Transfers		-0.5020	-0.5020	-0.5240	-0.4920	-0.3510	-0.4520
GA Subscription		0.8010	0.8010	1.7520	1.1930	1.7870	1.3049
Halbtax Subscription		0.8940	0.8940	0.8740	1.0360	1.0280	0.9705
Age		0.0010	0.0010	0.0350	0.0010	0.0010	0.0041
Bern-Capital (ÖV)		2.0000	0.0000	2.0000	0.0000	0.0000	0.6860
Mode Specific Constant (ÖV)		2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
Destination Choice (log (in value/1000))							
Jobs available		0.2660		0.3390			
Institutes			0.0940				
Retail Space					0.1750		
Population			0.2960		0.3840	0.1560	
Employment		0.3220		0.4130			
Recreational						0.1660	

The procedure of model validation and calibration is not explained as it is not relevant to current research. The following subsection explains the assumptions made for the study and the methodology adopted for the demand estimation of the Hyperloop network from NPVM.

3.2.3.2 Assumptions for the demand estimation

- The network operations have been considered from the year 2040.
- The structural data of the year 2010 from NPVM has been used to estimate the demand for the year 2040 due to the unavailability of the data.
- NPVM does not consider air passengers and active modes like walk and bike.
- No induced demand is considered for simplicity.
- Multimodal trips only within the public transport system and private transport are possible individually, not together.
- Current research does not take into account outbound/ inbound trips in Switzerland or the trips passing through Switzerland. The total outbound/ inbound or passing through demand consists of 9.13% of the total demand.
- The values of beta parameters are trip purpose-specific. They have been weighted averaged as per the data distribution.
- It is assumed that the station will be mounted on the main railway stations of the city which will make intermodal transfer smoother. This will lead to the assumption of similar access time to the train station.
- There are two cases considered for passenger tickets:
    - For the first case, the service is assumed to be operated under the General Abonnement (GA) similar to any other typical service in Switzerland.
    - For another case, ticket prices are assumed as explained in section 3.1.
- The routes were defined such that no transfers were required within the Hyperloop network.
- The headway of 6 mins was set similar to typical public transport line in Zurich. The headway was set similar to intra zone public transport service since it has been assumed that the Hyperloop service will be used for a daily commute.

3.2.3.3 Demand estimation for Hyperloop

As mentioned previously the current study assumes the scenario of 2040 without considering the induced demand. Since the demographic and structural data were not available for the year 2040, the modal share of 2010 is estimated and the same is applied to 2040 scenario. To apply the modal share of 2010 to 2040 scenario, calibration is performed while extrapolating shares.

The overall procedure is shown in Figure 3-3. As the figure shows, in the first step, data from the various sources is collected. These sources mainly include an online library of Federal Statistic office of Switzerland[15] for structural and demographic data, various documents of Swiss national passenger transport model (as mentioned in Table 3-4), Visum assignment model of NPVM of car and public transport for the mode choice variables. As the structural and demographic data is available only for the year

[15] https://www.bfs.admin.ch/bfs/en/home.html

2010 and not for 2040, initially 2010 mode shares are calculated for both existing network (no Hyperloop scenario) and public transport network with Hyperloop. And the same modal share has been applied to 2040 demand. The sole reason for re-estimating demand for the existing network was to calibrate the model. The calibration was required since the share are being extrapolated to the year 2040 and the complete data set was not available. This leads to the assumption of error term 'e_1' while extrapolating in-car utilities.

The unavailable dataset mainly includes parking time and parking cost variables. The available average value of 1.91 mins for smaller cities and 4.99 mins for bigger cities of parking search time and 0.68 CHF for smaller cities and 2.22 CHF for bigger cities of parking cost were added (Widmer et al., 2014). These average values were mentioned in the model description (ARE, 2014). Since these are average generic values, not the specific for each of the zones, this resulted into different demand estimation of existing networks than actual demand. Therefore, as mentioned previously an error term was introduced in the car utility 'e_2' to calibrate the model. After both the calibration the overall error in the car demand was found to be less than -2.43% (at OD level this may higher), which can be neglected.

Since there are no beta parameters available for the futuristic mode Hyperloop and estimation of beta parameters, itself is an exhaustive study, which is out of the scope the current research; existing public transport beta parameters are used for the demand estimation. It has been assumed that the Hyperloop will be part of the public transport network. This indeed adds up one more mode in the Swiss network of public transport besides train, regional bus, cable car, ferry and tram.

Once the calibration is achieved, the Hyperloop network is mapped in the public transport assignment of Visum model to generate new variables. This network was generated based on the MST algorithm between the aforementioned 12 cities. Figure 3-2 shows this network on the map of Switzerland.

Figure 3-2 Demand estimating network of Hyperloop

As mentioned in the assumptions of the demand estimation, the lines are generated in a way that no transfers will be required. Therefore, for the given network the lines generated are Lucerne-Geneva, St. Gallen- Geneva and St. Gallen- Lucerne. 6 minutes of headway is assumed for each of the lines.

As mentioned in the methodology, the link load profile will be used directly to determine the frequency of each line, peak hour models are being used for the demand estimation. This peak hour model considers morning peak hour from 0700 hours to 0800 hours. The peak hour models carry 7.2% demand of the car and 10.0% demand of the public transport (ARE, 2016). This demand has been extrapolated to the annual demand for the network generation phase since the average annual cost is considered for the B/C ratio determination. For this 251[16] working days in a swiss calendar year are considered.

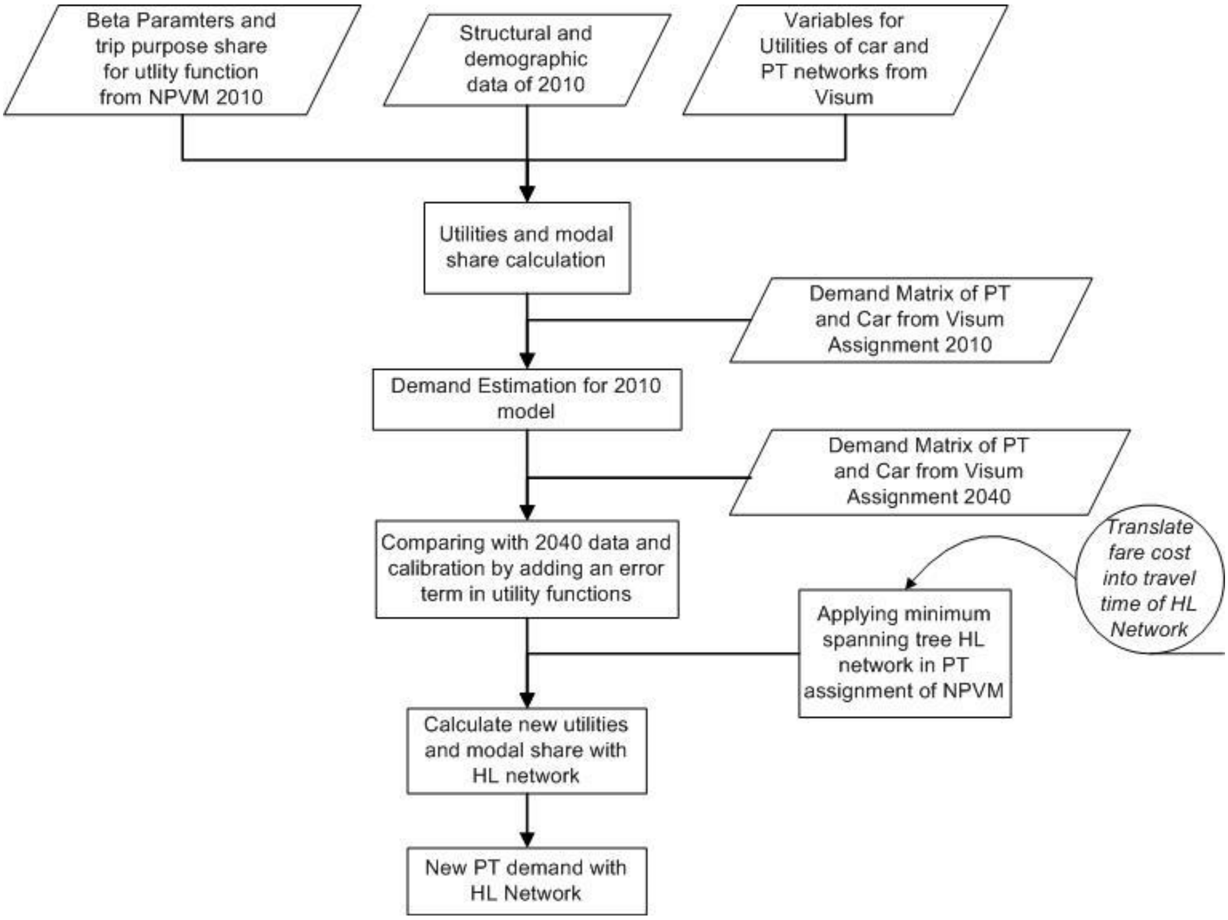


Figure 3-3 Procedure for demand estimation

The initial existing overall car share and PT share are found to be 67% and 33% respectively in peak hours. After applying the above-mentioned setting, new car and PT share are found to be 58% and 42% respectively. However, in 'with fare' scenario, 62% and 33% of shares are observed for car and PT respectively. Instead of considering the whole Switzerland OD matrix for the network design, the demand is aggregated at the city level for the above-mentioned cities. Out of which, for the three smaller cities i.e. Zug, Baden and Fribourg; the demand is aggregated at the canton level. Figure 3-4 and Figure 3-5 shows car demand and PT demand for existing

[16] https://www.arbeitstage.ch/EN/arbeitstage_2019.htm

networks respectively for the design area. Here, 27% car share and 73% PT share is observed.

Figure 3-6 shows the estimated new demand for a public transport network with Hyperloop network (‘without fare’ scenario). The new share of the car and PT are 20% and 80% are observed here. The figure also shows that the production and attraction from Baden are quite high as the size of the canton Baden is big. Figure 3-7 shows the Public transport network demand with Hyperloop being different fare price (‘with fare’ scenario). Here, car share of 24% and PT share of 76% is observed. It can be also noted that after applying fare pricing scenario all the OD pairs have shown a proportioned reduction in the PT mode share.

As all public transport modes have been merged as a single-mode in demand estimation of NPVM, it is not possible to estimate the mode-specific demand within public transport. Considering this limitation of NPVM, whole public transport demand has been used to generate network and routes.

In principle, the demand should be re-estimated as the network changes but considering higher VISUM computation time (more than 7 hours for the whole swiss network), only one iteration is made. This fixed demand is considered for network design.

Also, in the fare pricing scenario, the demand estimation cannot be carried out directly via changing the unit cost since all the public transport modes are merged as a single mode. Therefore, the fare has been converted into travel times via multiplying the VoT values. These travel time increase has been made for the residual values of fare i.e. 0.07 (2010 rates) CHF/km since existing estimation already considers 0.20 CHF/km. For both the scenarios, the same mode shares were applied to 2040 demand.

The following section explains the existing travel time for Car and PT between the above mentioned stations.

3.2.4 Existing travel time

The existing travel times are extracted from the Visum networks. The travel times for Car and PT are shown in Figure 3-8 and Figure 3-9. For PT only in-vehicle travel time is considered, while for the car uncongested travel time is considered. The scale in the figure shown is in absolute minutes. It can be observed that between any pair of the cities the travel time of the car is less than PT despite considering only in-vehicle travel time for PT. This gives an indication of Hyperloop being part of public transport will have higher B/C ratio.

Thus, the chapter answers sub-research question 1 and develops the input for the model. In the following chapter, the results have been explained for the network design algorithms.

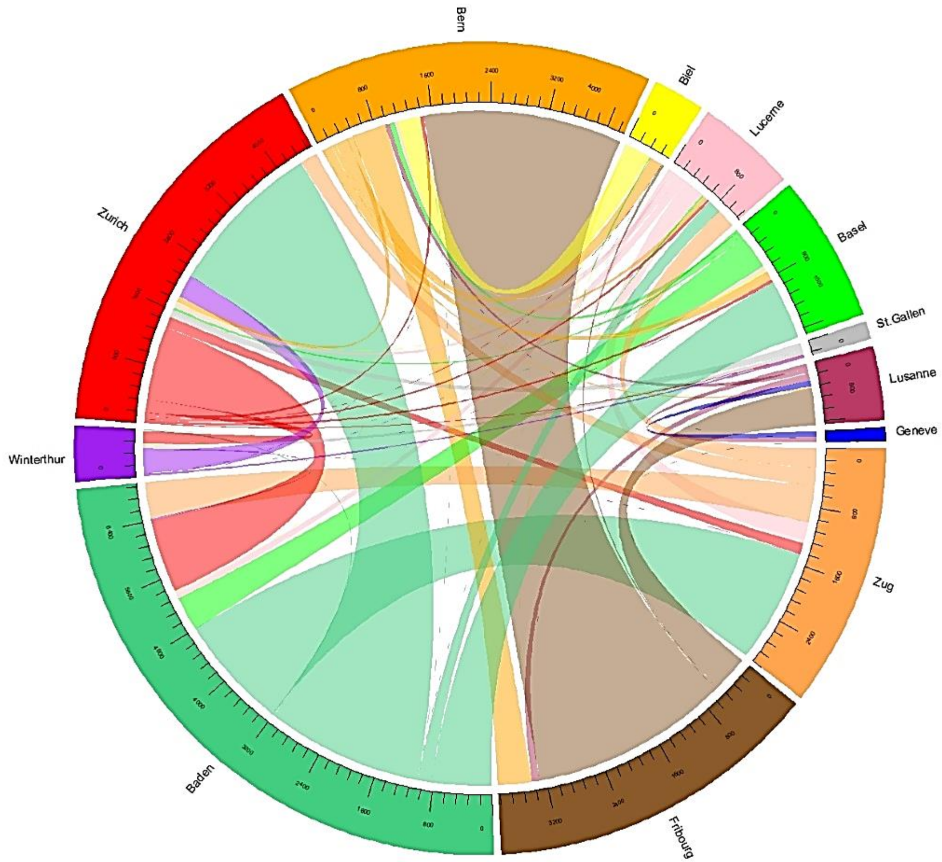


Figure 3-4 Existing network car demand 2040

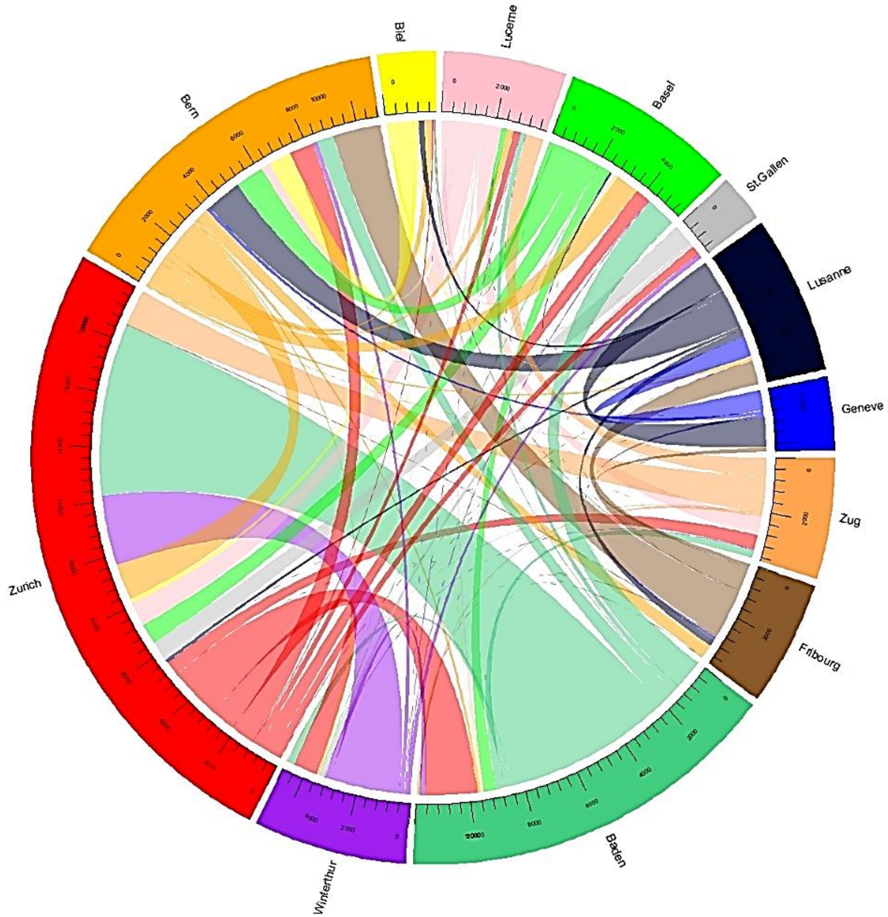


Figure 3-5 Existing network PT demand 2040

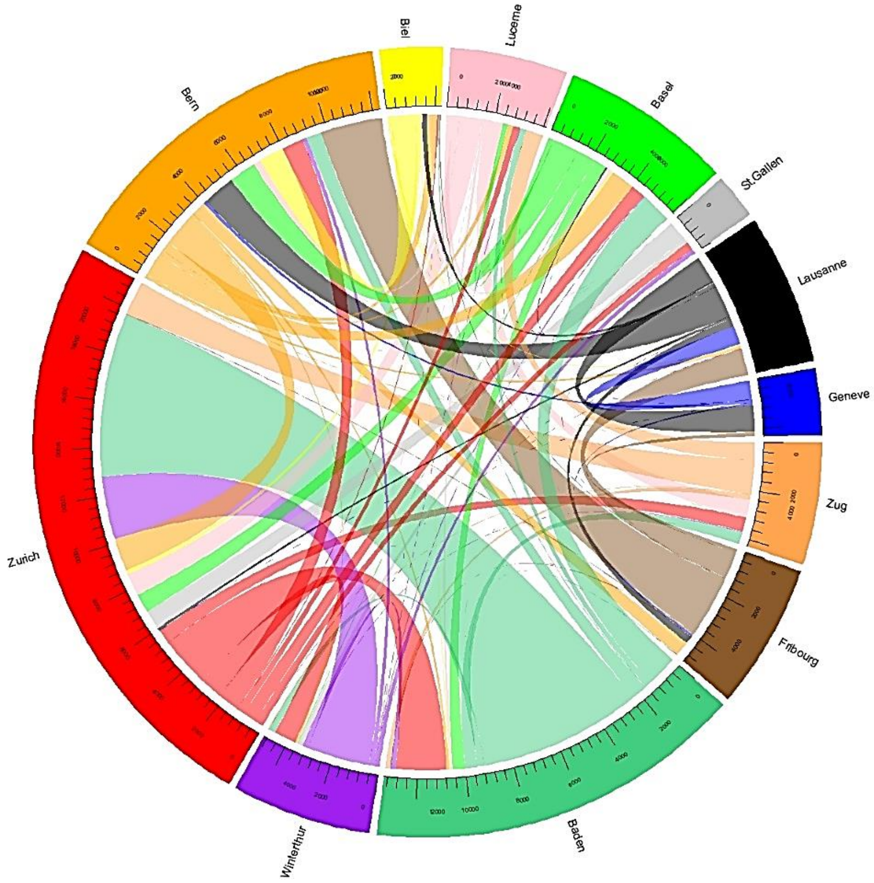


Figure 3-6 PT Demand with Hyperloop network: 'without fare' scenario'

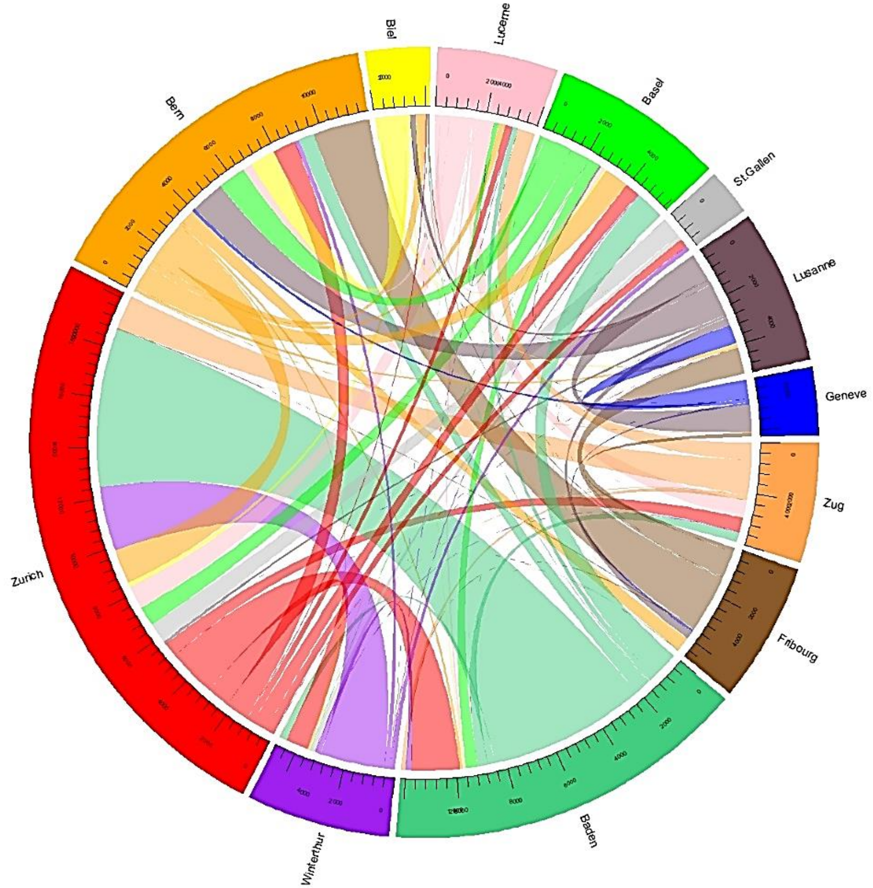


Figure 3-7 PT Demand with Hyperloop network: 'with fare scenario'

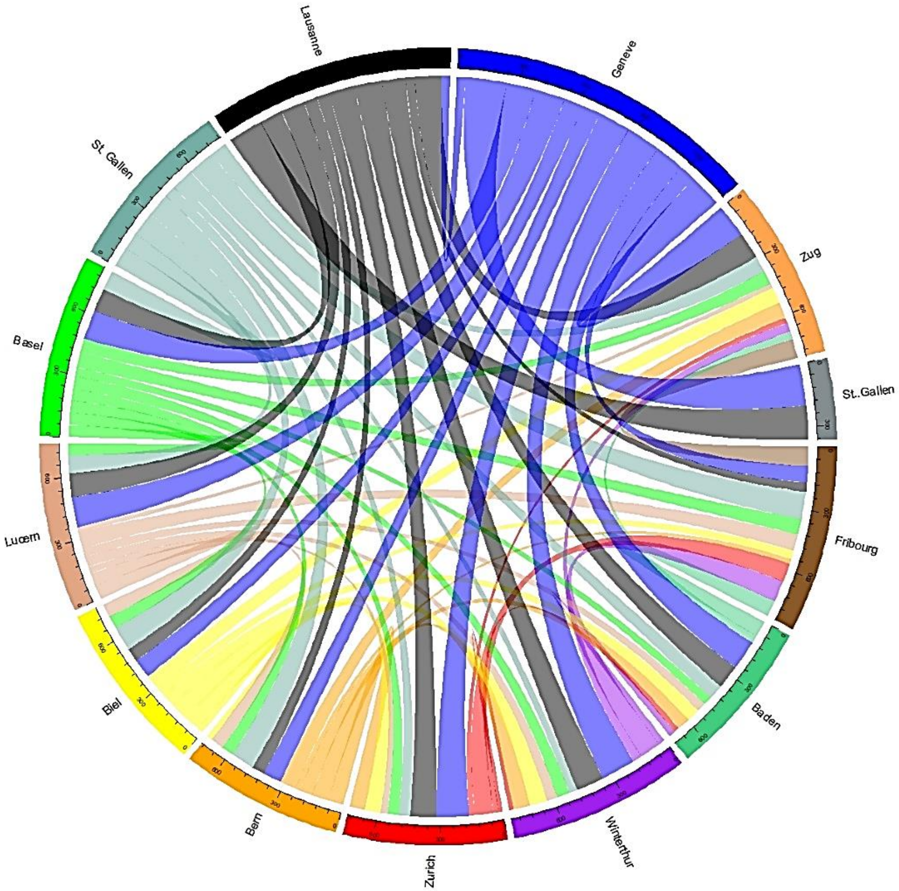


Figure 3-8 Car travel time from NPVM

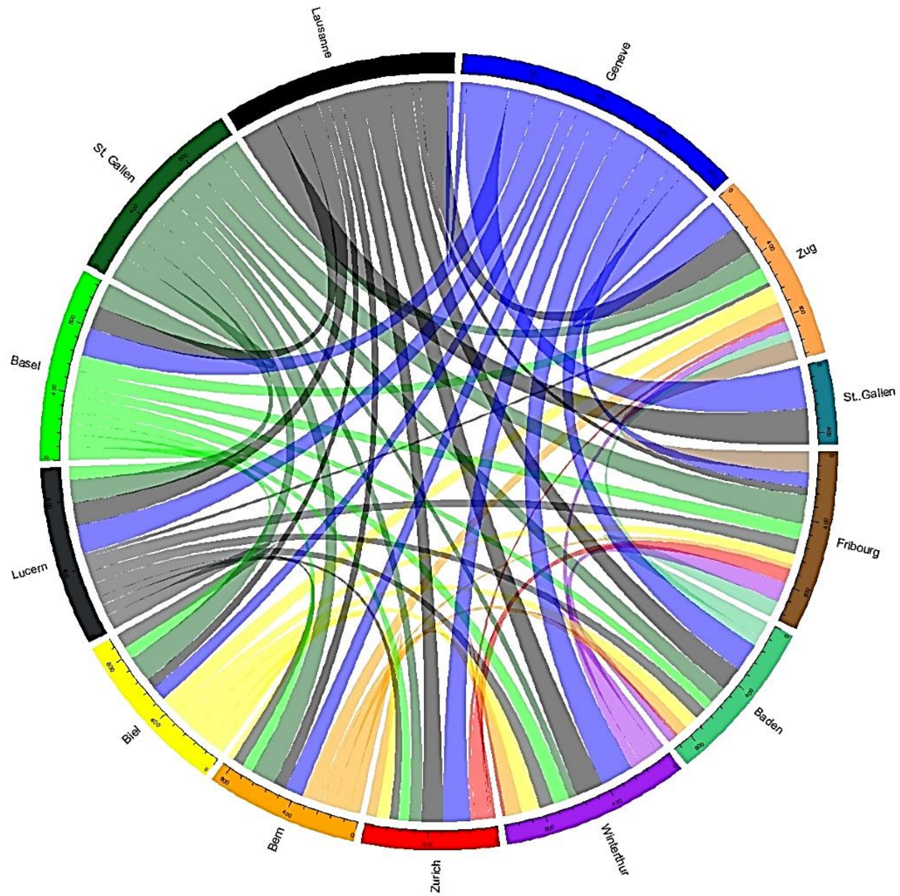


Figure 3-9 PT travel time from NPVM

3.3 Assignment with NPVM

As mentioned in chapter 2, the assignment procedure is performed with the regional transport network. As mentioned in the demand estimation, NPVM assignment is performed in Visum 16.01-4 version. The characteristics of the networks are described in section 3.2.3.1.1. The national transport network of Switzerland is bifurcated in two networks i.e. car network and PT network. The assignment for both the networks is performed separately. For evaluating Hyperloop scenarios and base scenario the peak hour models of 2040 are considered.

The network of the car also includes freight traffic by road network. The equilibrium is achieved based on the Lohse model in the road network. The idea of Lohse model is based upon the learning process of road users over several iterations (Schnabel & Lohse, 1997). The first iteration starts with “all or nothing assignment”, after which the travel time realized from the previous journey are also considered for the next iteration. To estimate the travel times for each route values of parameters in volume delay function are added in 8 different combinations. These values depend upon the characteristics of the road link like speed and capacity. The detailed explanation of the assignment procedure can be read in the Visum manual. Since the current research does not involve modification in the road network, it is not relevant. The only difference will be in the demand of road networks in the different scenario of the base, ‘without fare’ Hyperloop and ‘with fare’ Hyperloop.

The characteristics of the PT network is explained in section 3.2.3.1.1. The assignment model of PT networks in Visum does not take into account the capacity constraints. The assignment procedure is performed in order to minimize the perceived journey time. The perceived journey time is derived by assigning the weights to the components of the travel time. These weights are mentioned in Table 3-5. The walk, access and egress time weights are almost three-fold of the in-vehicle time. The highest weight is given to the transfer penalty. With each transfer, 21 mins are added in the overall journey time. In this case, if the reduction of the travel via Hyperloop is greater than 21 mins passengers will be transferred to the Hyperloop. From Figure 3-9, it can be overserved that most of the links will have a reduction in journey time, which is greater than 21 mins.

Table 3-5 Weights of the travel time components in the assignment procedure

No.	Component of the travel time	Weight
1	In-vehicle time	1.00
2	PuT-Aux ride time	1.00
3	Access time	2.70
4	Egress time	2.70
5	Walk time	2.70
6	Origin wait time	1.39
7	Transfer wait time	0.50
8	Number of transfers	21min

Once the assignment is performed, the network-wide (global) values of travel time components mentioned in Table 3-5 can be extracted. To evaluate them they can be multiplied with the respective VoT mentioned in section 3.2.2.3. However, here it is important to mention that the in peak hour, PT network capture 10% demand of the daily, while car network 7.2% of the daily demand. In order to compare scenarios, the values extracted from the assignment, first need to be extrapolated for daily values and then needs to be added for the car network and PT network of the respective scenarios.

4 Results

After developing inputs for the network design, the current chapter explains and analyses the results of the developed algorithms of the network design. The chapter explains the results of the network generation in section 4.1 followed by routes and frequency in section 4.2. Section 4.3 shows the assignment results. The CBA is covered in section 4.4 followed by sensitivity analysis in section 4.5.

4.1 Network generation

The Network Generation is developed by link swapping and link deletion algorithm. The purpose of network generation is to identify the links which are feasible for Hyperloop network i.e. B/C ratio is greater than one. As explained in the previous chapter, there are two cases with demand estimation, which leads to four different scenarios (chapter 3). Both the algorithms are initiated from completely opposite starting points. Link swapping starts with MST based on the cost i.e. minimum cost network, while link deletion starts with a fully connected network i.e. all nodes are connected to all other nodes (maximum benefits network). However, for a given case, both the algorithms generate the same output despite having completely opposite starting points and processes.

4.1.1 Link swapping

As mentioned, link swapping starts with MST based on cost. If the B/C ratio of the network is greater than one, then the algorithm keeps adding the link to the network, until it reaches below one. These links are added from a non-generated set of links based on maximum demand. When it reaches below one, the swapping is initiated. The swapping process is followed until convergence is achieved i.e. the added link is the same as the removed link.

4.1.1.1 Link swapping: 'without fare' scenario

For the given case, the results of the link swapping algorithm are shown in Appendix 6. The algorithm is initiated with the highest B/C ratio of 1.73. This can be observed from Figure 4-1. This indeed is the highest B/C ratio, since the network has the least cost. The cost of the MST network is the least, considering the minimum length of the network. For the first six iterations, the algorithm keeps adding link till the B/C ratio reaches below the value of one. After this, the link swapping starts for the next four iterations, until the Baden-Brugg-Winterthur link is removed. This link becomes the convergent link in the fourth iteration since it gets added and removed in the same iteration. Running more iterations of this algorithm will only lead to cycles of adding and removing the same link. Figure 4-2 shows the graphical representation of the network.

The algorithm develops all links that can keep the B/C ratio above one for the network. The only link which can be debatable is the link between Zurich and St. Gallen. This is because of the connection between Zurich-Winterthur-St. Gallen is geographically more convenient compared to generated connections Winterthur-Zurich-St. Gallen. The adjacency matrix of the network has been attached in Appendix 7-9.

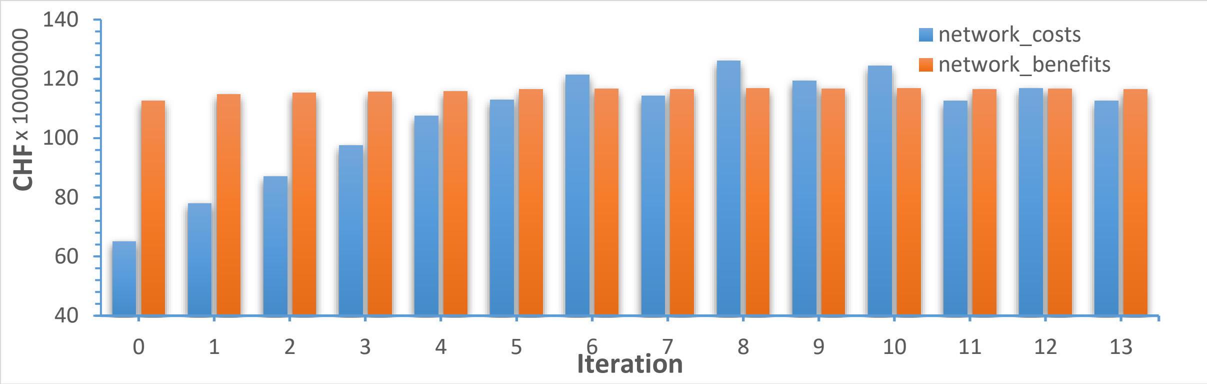


Figure 4-1 Results of network generation: link swapping 'without fare' scenario

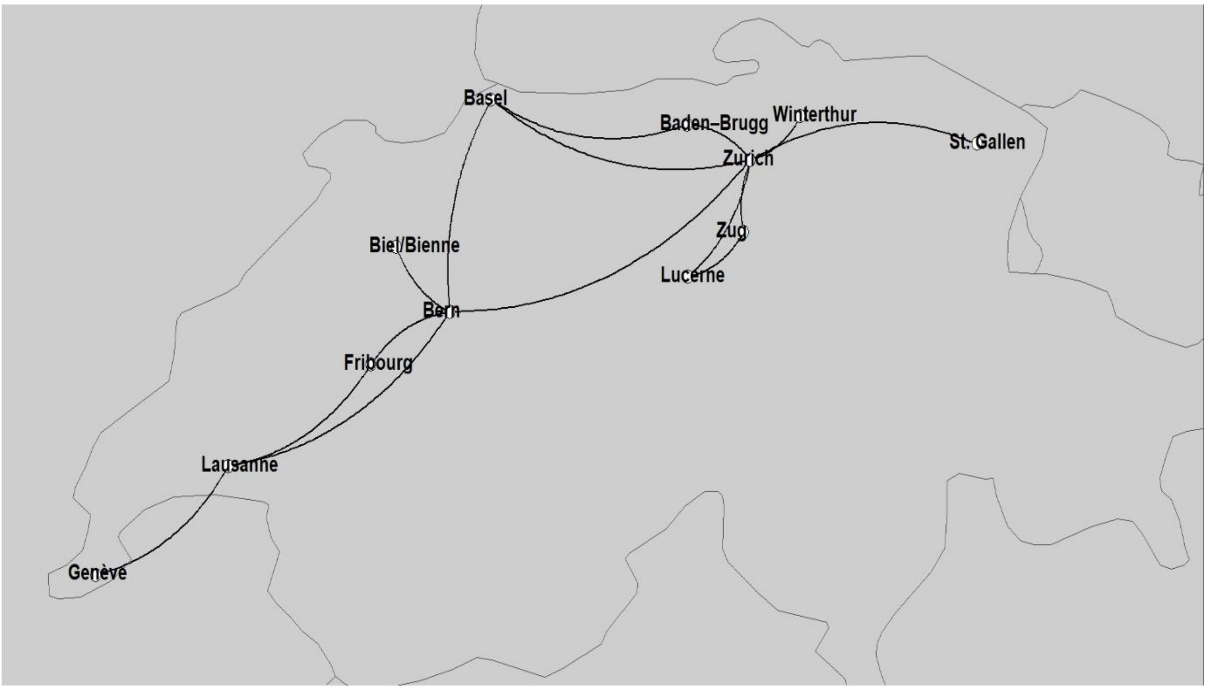


Figure 4-2 Network of scenario: 'without Fare'

4.1.1.2 Link Swapping 'with fare' scenario

For 'with fare' scenario, the demand has been reduced, this turns into a reduction of benefits. Considering this argumentation, in principle, the network should be less connected compared to the previous one. The results show this expected output, as shown in Figure 4-3.

The links were added for the first five sub iterations compared to seven in the previous case. Also, one less iteration was required to perform to converge than the previous case. The algorithm converges with the B/C ratio of 1.02. The adjacency matrix has been attached in the appendix and the graphical representation shown in Figure 4-2. Baden-Brugg-Bern becomes the convergent link.

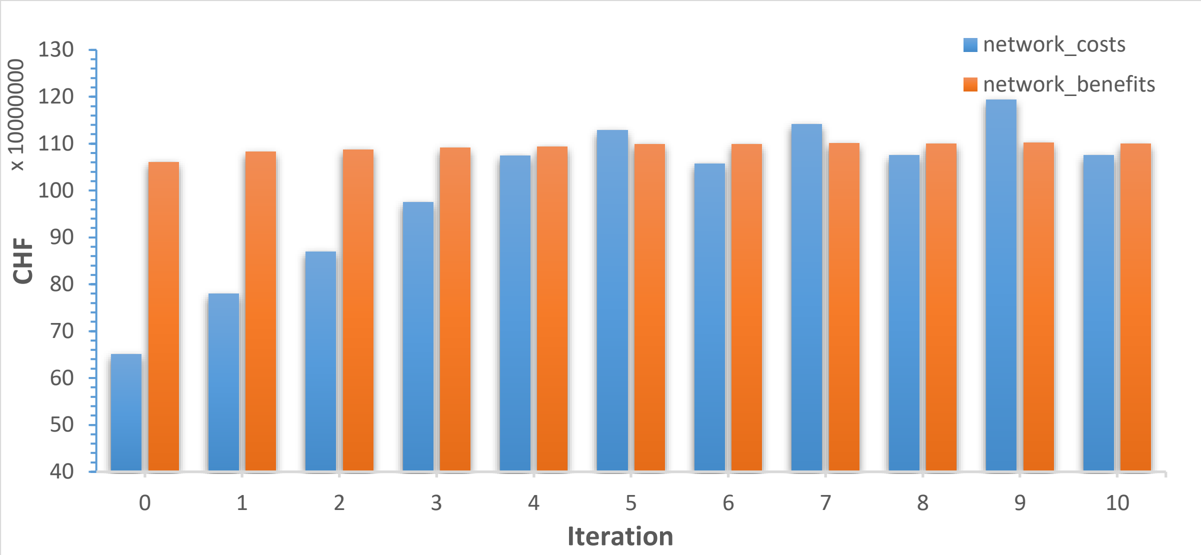


Figure 4-3 Results of Link swapping 'with fare' scenario

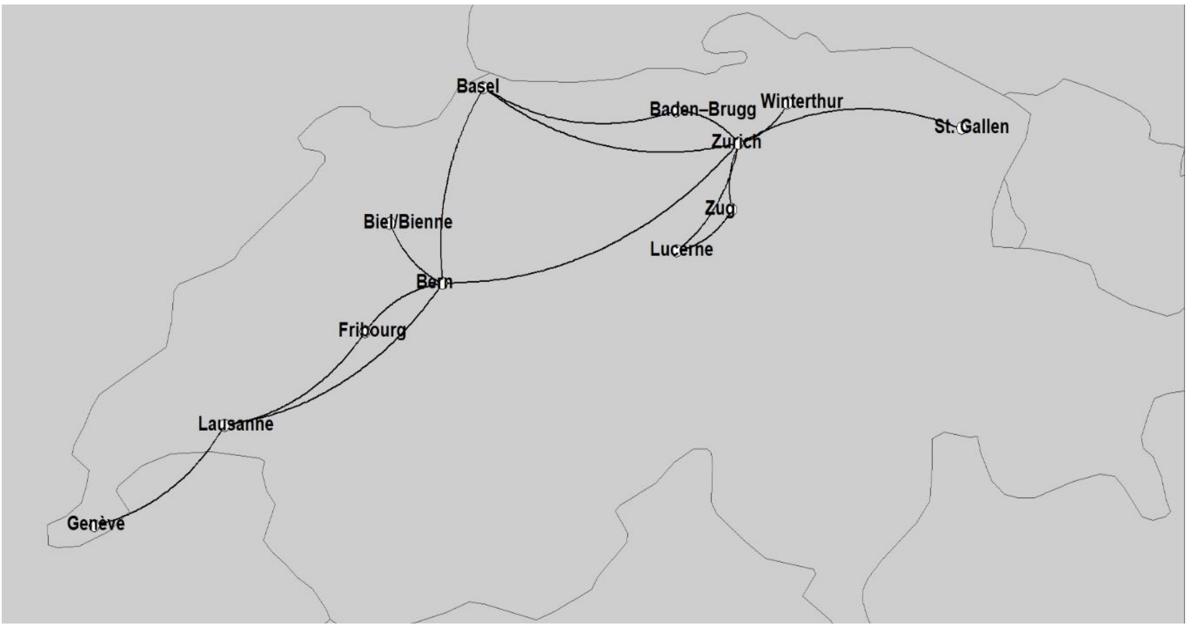


Figure 4-4 Network of 'with fare' scenario

4.1.2 Link deletion

Similar to the previous section, this section also explains the results of the link deletion algorithm with both the demand cases. The algorithm starts with a fully connected network. This will have a minimum B/C ratio. Throughout the algorithm, the network keeps removing the link with the minimum flow until the B/C ratio reaches a value greater than one. With every deletion of the link, the flow gets re-assigned with the shortest path. With every deletion of the link, the B/C improves for the network since the cost of the infrastructure reduces significantly compared to the increase in the travel time savings. The algorithm could be extended until it achieves a maximum B/C ratio by removing more links, but this will develop mono-centric or bi-centric networks. This will have more routes and higher vehicle cost in the following step.

4.1.2.1 Link deletion: 'without fare' scenario

As mentioned, contradictory to the previous algorithm, this algorithm starts with a fully connected network, which essentially forms minimum B/C ratio, since the network is fully connected and thus, has the highest cost. The algorithm converges at the 47th iteration, where the B/C ratio reaches above 1. However, the network generated with this algorithm is similar to the link swapping. The convergence similarities between link swapping and link deletion have been discussed in the limitations section. Figure 4-5 shows the graphical representation of the algorithm process in which it can be observed that the algorithm develops the network in a way that the cost is being constantly reduced and travel time savings are improved. The output of the algorithm is similar to the network generated section 4.1.1.1 and with the same B/C ratio as well.

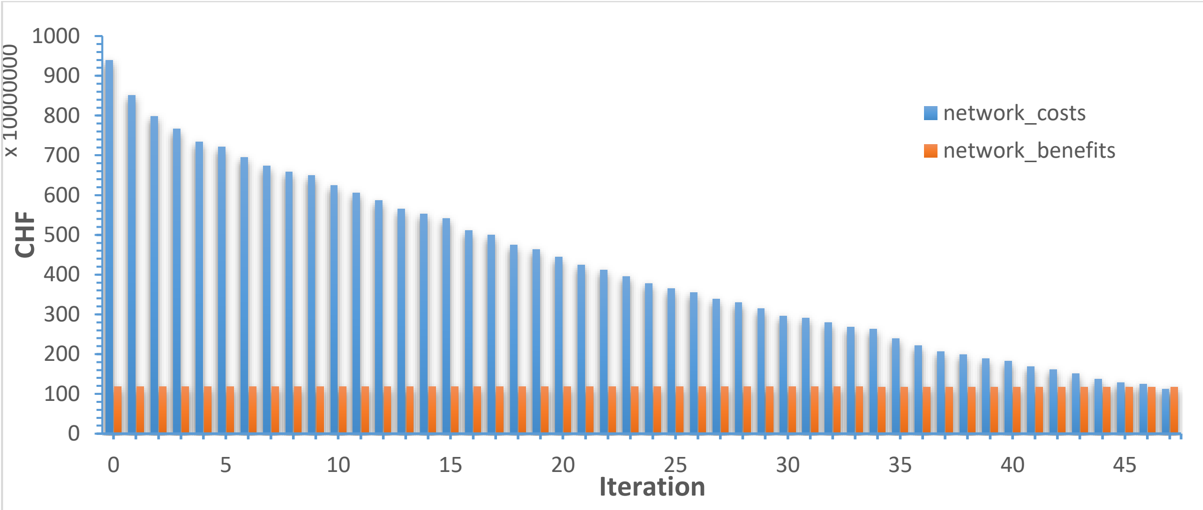


Figure 4-5 Results of scenario link deletion 'without fare'

4.1.2.2 Link deletion: 'with fare' scenario

Similar to sub-section 4.1.1.1, the algorithm converges after one more iteration than the previous case. The convergent B/C ratio is similar to Link swapping 'with fare' scenario (sub-section 4.1.1.2), which is 1.02.

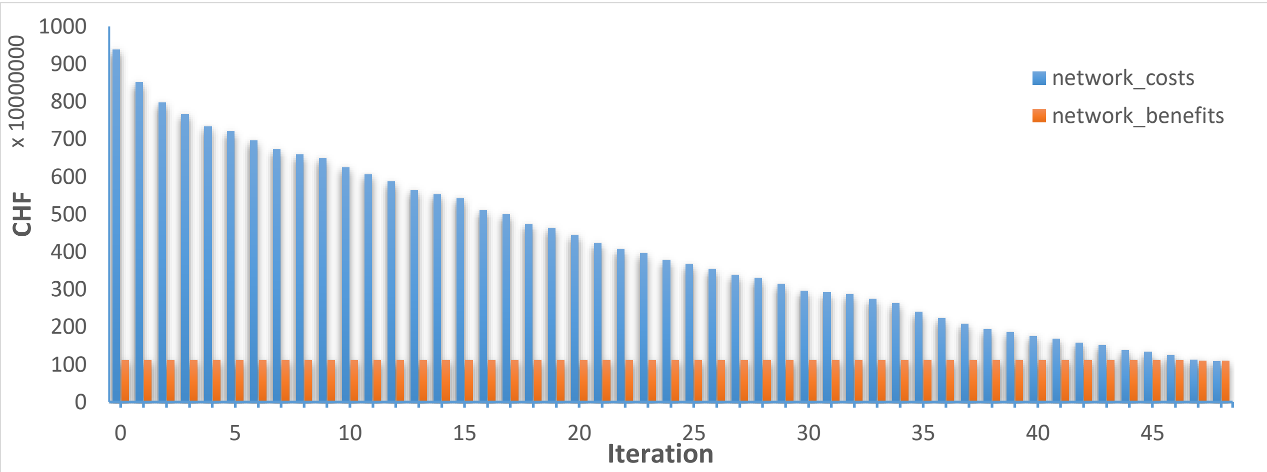


Figure 4-6 Results of link deletion 'with fare' scenario

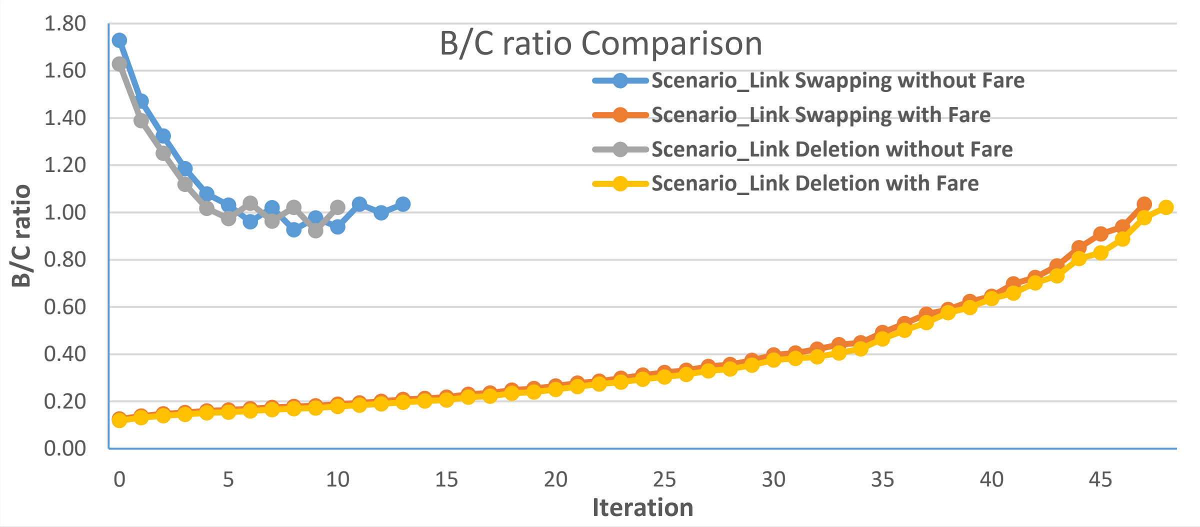


Figure 4-7 B/C ratio comparison

Figure 4-7 shows all the B/C ratios generated for all the scenarios. It has been observed that for the same inputs, both algorithms converge at the same B/C ratio for the networks. As mentioned before, with the fare scenario since the demand is lowered, a reduced link network is generated. The tables in the appendix can be helpful to understand which links are added /deleted/ swapped during each iteration.

After Network Generation, the following section of the chapter explains the route generation.

4.2 Route design

Once the network is generated, the routes will be designed in this step. As mentioned in the methodology chapter the route design algorithm follows Mandl's approach. The routes identified are based on the longest shortest path of the network and the objective is to minimise the number of transfers.

Since only two networks have been realised, route design is also performed only on these two networks. However, these two networks have a difference of just one link. Considering the similarity of the networks, the routes remain the same for both networks. The difference between the routes of both networks is only in terms of the number of transfers. Table 4-1 shows the list of routes generated for both networks with the route design algorithm. The results of routes show redundant links in the networks, which will be removed after determining the set of routes.

Table 4-1 shows that three sets of lines could cover the entire network. Between these lines, Zurich turned out to be the station with the maximum number of transfers. Considering Zurich as the transfer point between the lines, the portion of the lines on each side are switched as explained in the methodology. This leads to the generation of eight scenarios (2^3=8). Figure 4-8 shows a comparison of the number of transfers with each set of routes. Since the demand of the Fare pricing scenario is proportionately lowered, the number of transfers is also comparatively low for each of the scenarios. In both cases, scenario-3turns out to be the optimum one, with the lowest number of transfers i.e. 2195 and 2127 for without Fare and with fare scenarios, respectively.

Table 4-1 List of routes

Scenario	Lines	Routes
1	1	Lucerne, Zug, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	2	St. Gallen, Zurich, Bern, Biel/Bienne
	3	Winterthur-Zurich
2	1	St. Gallen, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	2	Lucerne, Zug, Zurich, Bern, Biel/Bienne
	3	Winterthur-Zurich
3	1	St. Gallen, Zurich
	2	Winterthur, Zurich, Bern, Biel/Bienne
	3	Lucerne, Zug, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
4	1	Lucerne, Zug, Zurich
	2	St. Gallen, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	3	Winterthur, Zurich, Bern, Biel/Bienne
5	1	St. Gallen, Zurich
	2	Winterthur, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	3	Lucerne, Zug, Zurich, Bern, Biel/Bienne
6	1	Lucerne, Zug, Zurich
	2	Winterthur, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	3	St. Gallen, Zurich, Bern, Biel/Bienne
7	1	Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	2	St. Gallen, Zurich, Winterthur
	3	Lucerne, Zug, Zurich, Bern, Biel/Bienne
8	1	Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève
	2	Lucerne, Zug, Zurich, St. Gallen
	3	Winterthur, Zurich, Bern, Biel/Bienne

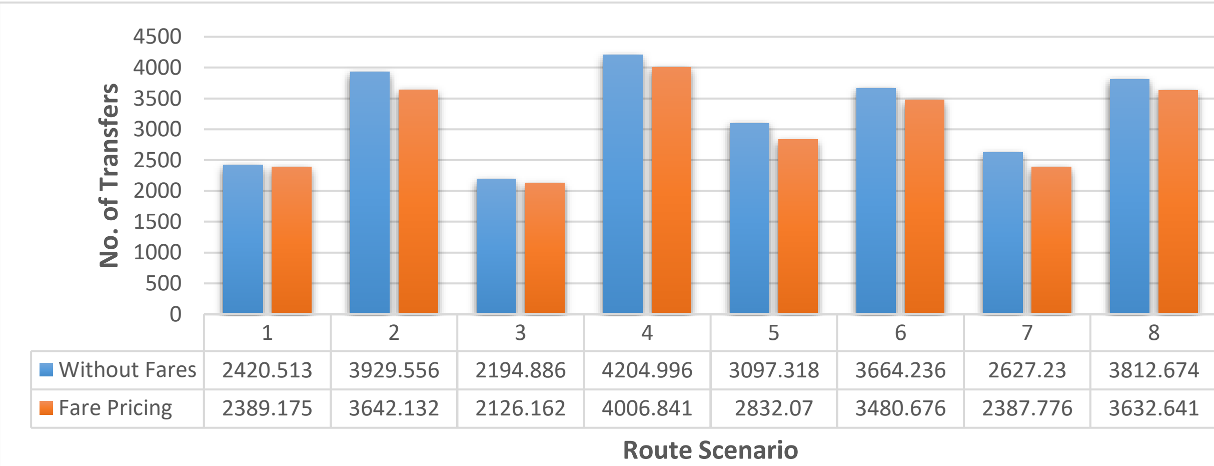


Figure 4-8 Number of transfers within routes

For scenario 3, along with the set of routes, the load profile has been plotted in Figure 4-9 and Figure 4-10. In both figures, it can be observed that the load is higher towards major cities, namely Zurich and Bern. This observation is in-line with the input demand of the morning peak hour. The morning peak hour demand showed a significant share of commuting and educational trips towards major cities.

Due to the consideration of larger canton regions of Baden-Brugg (aggregation of 432 zones in Aargau) and Fribourg (canton 436 zones), the flow from these cantons turns out to be very high. This leads to unrealistic frequency determination. Also, for the network generation and route design, the whole public transport demand was considered. This consideration was due to the limitation of demand estimation model NPVM to estimate the mode-specific demand. Though while estimating demand, it was observed that the Hyperloop Network generated 15%[17] of the passenger-kilometres. Given this argument, 15% of the maximum load is considered for the frequency setting of each of the lines. The grey line (up direction) and the yellow line (down direction) in Figure 4-9 and Figure 4-10 shows the service capacity of without fare and 'with fare' scenario respectively.

The frequencies of each of the lines are shown in Figure 4-11 with a graphical representation of the lines for both scenarios. These frequencies are rounded off to the nearest 0.5. The figure shows the graphical representation of the generated network with routes and frequency of respective lines. Based on the adapted approach for frequency determination, it is quite evident that the line underutilised in terms of frequency. This mainly because only one pair of stations are selected for line one. As mentioned in the network generation section 4.1.1, the unexpected link is Zurich to St. Gallen. Comparing with the developed Hyperloop network to Swissmetro network (Figure 1.1), there was also a direct connection between Lucerne and Bern instead of Bern to Zurich in Swissmetro. However, a higher demand between these two cities led to the generation of a direct link in Hyperloop Network.

The following sub-section of the chapter shows the results generated from the assignment model of NPVM. The number of vehicles required is part of the cost-benefit analysis.

[17] 7345614 pass-km by Hyperloop of 905,019.40 pass-km total network. This can also depend upon the setting of frequency while estimating demand.

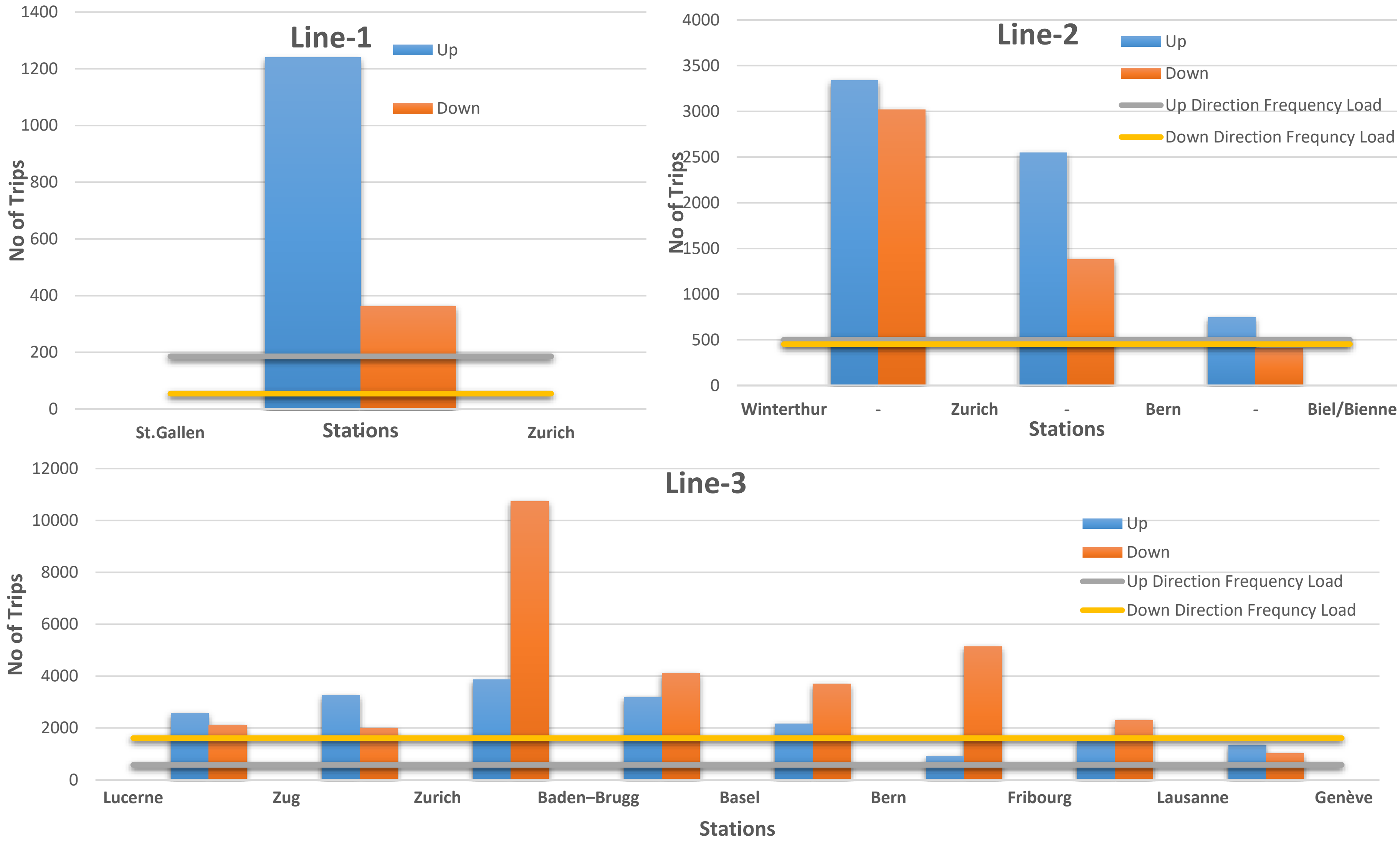


Figure 4-9 Load profile and service capacity of the lines: 'without fare' scenario

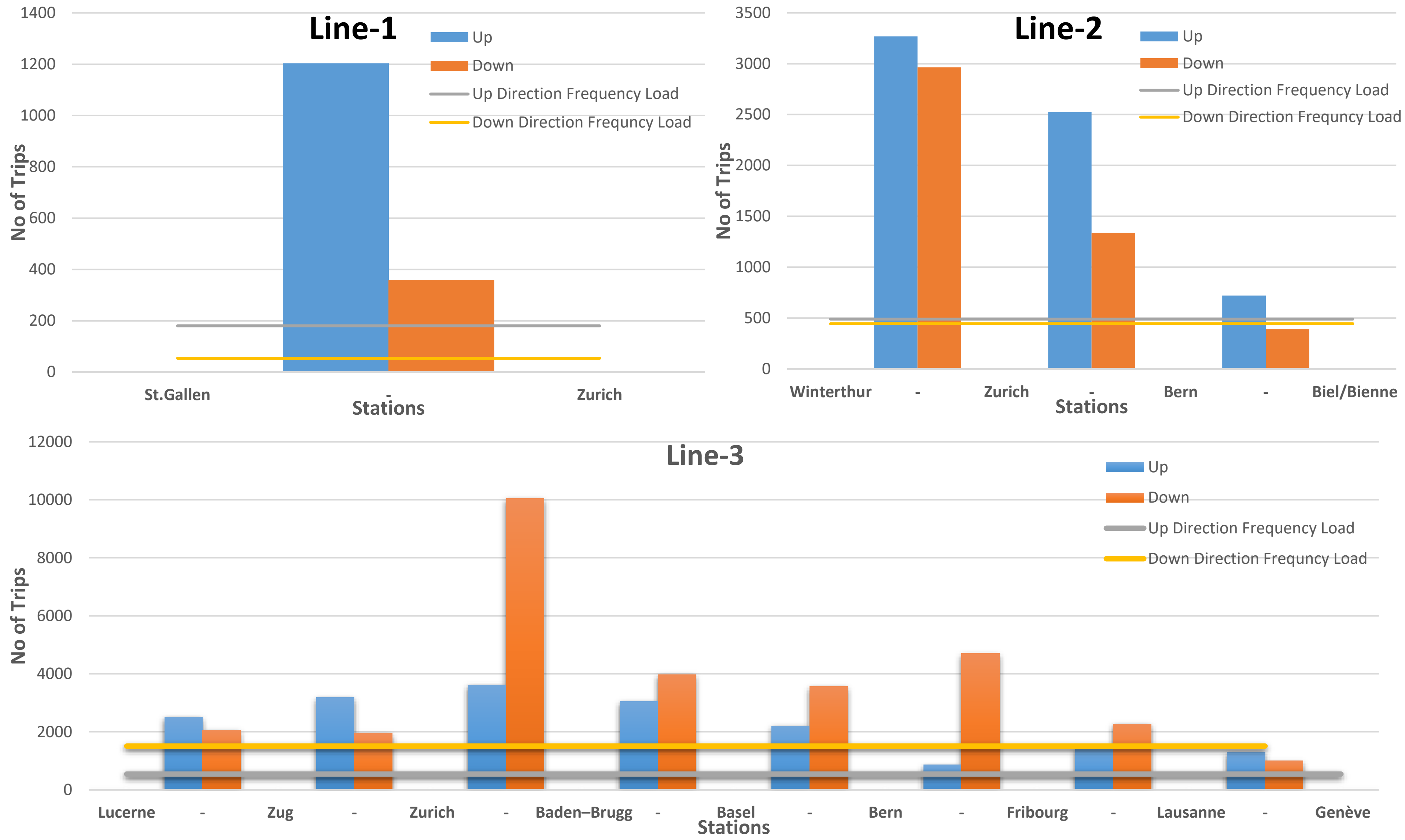
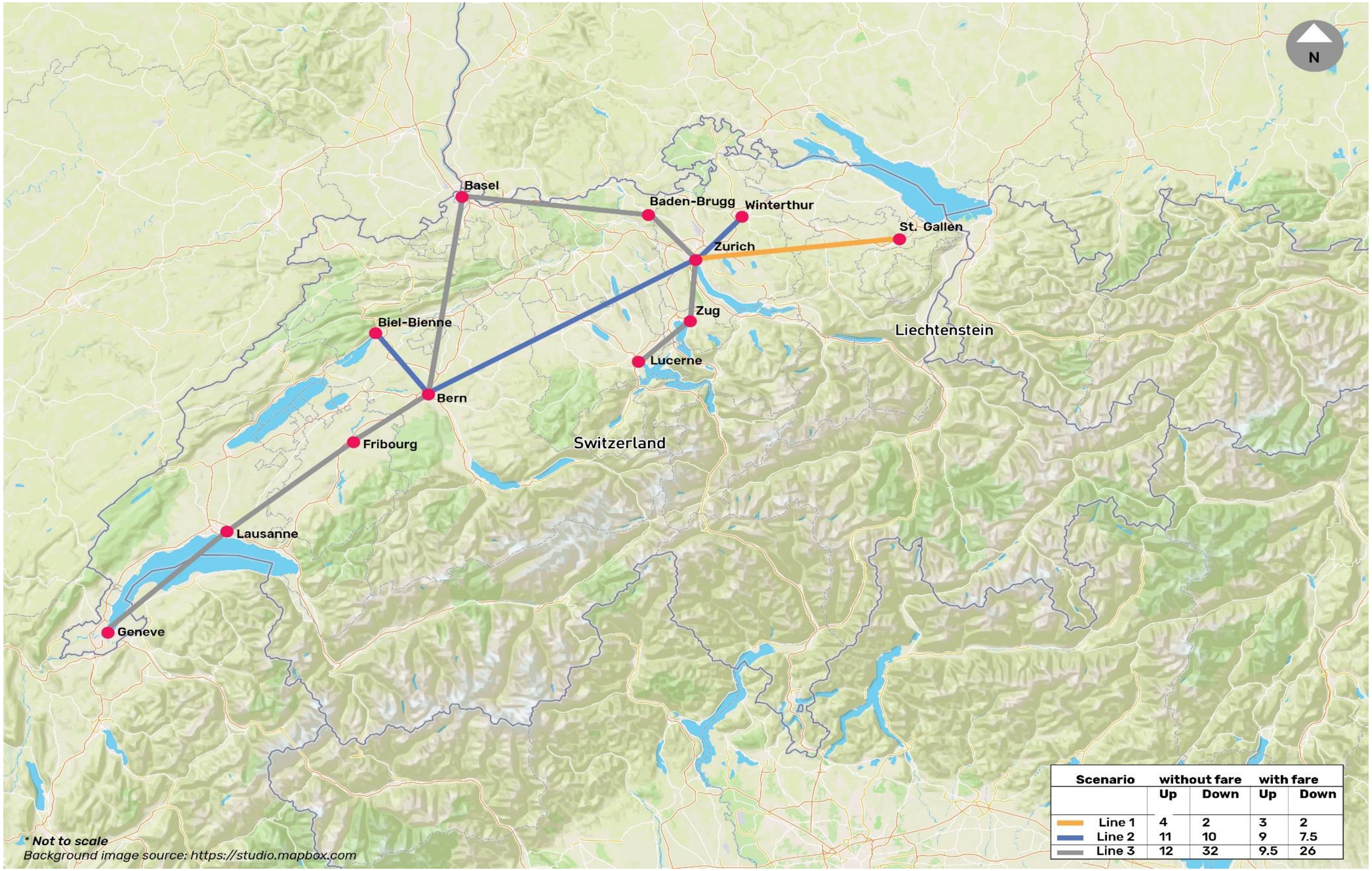


Figure 4-10 Load profile and service capacity of the lines: 'with fare' scenario



Scenario	without fare		with fare	
	Up	Down	Up	Down
Line 1	4	2	3	2
Line 2	11	10	9	7.5
Line 3	12	32	9.5	26

Figure 4-11 Geographical map of Switzerland with Hyperloop Network including the routes and frequency

4.3 Assignment results

The assignment is performed in the PTV Visum 16.01-04 version. The aforementioned network of Hyperloop is formed with the public transport network of Switzerland for the assignment. The assignment is performed for the peak hour (0700 hours to 0800 hours) of an average working day in the year 2040. These assignments are performed with the new estimated demand for both scenarios. As mentioned in the assumptions of the study, the demand matrix has been reduced to the border of Switzerland only. The zones outside the border are not considered. This led to performing assignment again for the base case as well.

The assignment results of the public transport network showed the mean perceived journey time of 1h 32mins, 1h 42mins and 1h 46mins in base scenario, without fare Hyperloop scenario and ‘with fare’ Hyperloop scenario respectively. However, comparing them directly will not lead to actual evaluation. The increase in the mean perceived journey time is due to weights of the travel time components especially transfer penalty and transfer weight time (refer Table 3-5) in assignment procedure. This leads to the passenger from inner regions to make a longer journey via Hyperloop and will result in perceived journey time. However, this increase does not exceed than the decrease in the mean journey time of car network. The actual comparison can be made by only adding total travel times of car and PT network and multiplying with their respective VoT. This is followed in travel time savings section of the CBA (refer section 4.4.5).

The comparison of pass-hours for both the networks is shown in Figure 4-12. The overall mean journey time for both Hyperloop cases is higher since the demand is also higher. The reduction in pass-hours of a car is observed to be 17.56% and 9.66% for ‘without fare’ and ‘with fare’ cases respectively. The passenger hours of public transport are based on the ride time of the network. The ride time includes access time, in-vehicle time, transfer wait time and egress time. The ride hours of public transport are higher by 26.16% and 42.93% for the respective cases. However, the mean speed of the public transport network is reduced by 1km/hr for both Hyperloop cases due to addition of Hyperloop. This reduction is significant for the network of 30,530 routes and 17,689 stops.

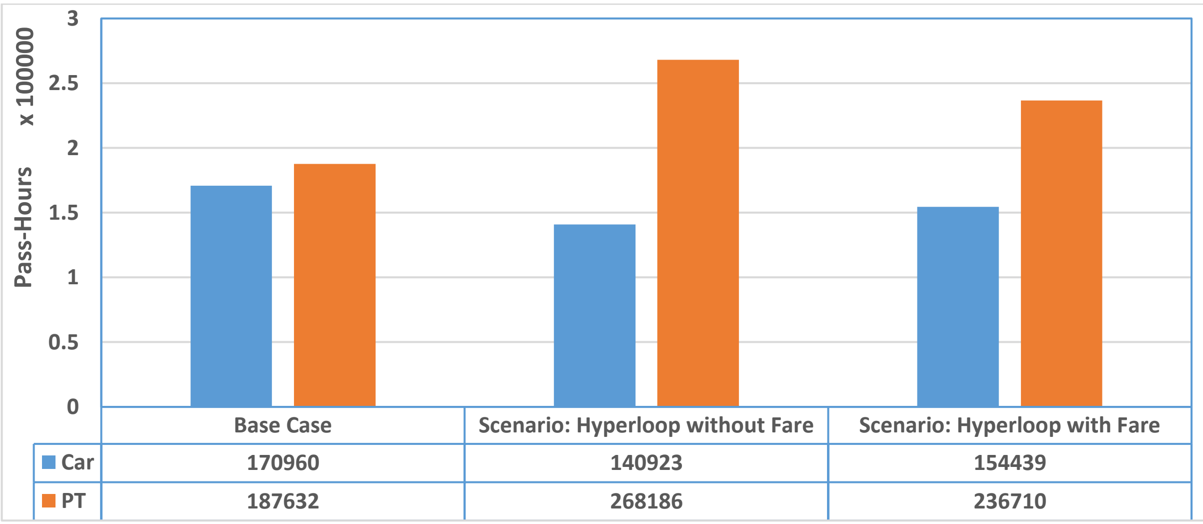


Figure 4-12 Simulation results: Pass-hours

Figure 4-13 shows the comparison of the pass km for all scenarios with Car and PT networks. 'Without fare', the scenario shows higher pass-km than the base scenario. The Hyperloop scenario shows a 33% increase in the pass-km compared to the base scenario. This will lead to a reduction in the operational cost of car network by 17.46% (cost 0.16CHF/km)[18]. Similarly, 'with fare' scenario, 9.36% reduction is observed in car operational cost. Here, it is also important to note that the pass-km for PT networks, shown in Figure 4-13, is the ride distance. This includes the distance for access (the distance within stop area) as well.

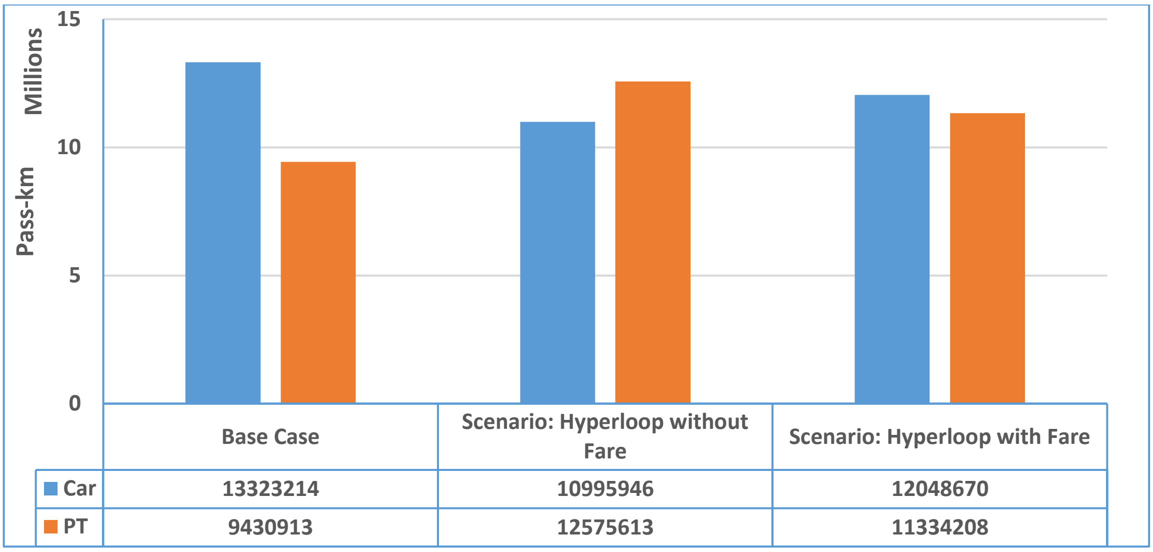


Figure 4-13 Simulation results: Pass-km

After performing assignments of the networks, the networks are assessed with cost-benefit analysis in accordance with the Swiss norms. The following section explains the same.

4.4 Cost-benefit analysis

The CBA is performed in accordance with the Swiss CBA norms. The analysis performed in this section is not complete in terms of consideration of types of cost and benefits. However, this may be considered as the starting point for the discussion of CBA for Hyperloop. The types of costs and benefits considered are limited to (i) initial infrastructure cost, (ii) maintenance cost, (iii) operational cost (iv) travel time savings (v) fare revenue.

Table 4-2 Summary of CBA

No	Description	without fare (BCHF)		with fare (BCHF)	
		Costs	Benefits	Costs	Benefits
4.4.1	Infrastructure Cost	51.59		51.52	
4.4.2	Maintenance Cost	02.16		02.14	
4.4.3	Replacement Cost	02.92		02.84	
4.4.4	Operational Cost	06.89		06.82	
4.4.5	Travel Time Savings		33.57		03.89
4.4.6	Fare Revenue		72.95		97.46
	Total	*61.98*	*106.52*	*61.78*	*101.35*
	B/C ratio	**1.69**		**1.61**	

18 (ARE, 2014)

It is important to mention that the analysis does not consider an increase in the operational cost of the existing public transport network or a decrease in the operating cost of cars. Since the demand for the car network is reduced, the maintenance cost of the same will be reduced as well. However, this is not considered in the analysis. The analysis period is performed for 50 years, assuming the infrastructure construction duration would be five years (2036-2040). The operations will start in the year 2040. The benefits from 2040 to the next 49 year i.e. up to the year 2089. Table 4-2 shows a summary of the costs and benefits. The costs and benefits are in the net present value of the year 2040 i.e. discounted with a 2% discount rate to the reference year. The B/C ratio turns out to be 1.69 for the without fare scenario and 1.61 for the 'with fare' scenario. These numbers show significant gains over costs incurred. However, it is important to mention that these numbers are not part of the complete analysis and an exhaustive number of assumptions are involved in this analysis, which can change the output or interpretation largely.

Figure 4-14 and Figure 4-15 show the cashflow of discounted benefits over the analysis period. Both the figure shows a drop in the benefits in the year 2059 and in the year 2079 due to replacement cost of vehicles, propulsion system and ventilation. Similarly, the drop in the benefits in the year 2064 is due to the replacement of the solar panels. The internal rate of return (IRR) turns out to be 3.30% and 2.90% for 'without fare' and 'with fare' scenario respectively. The discounted payback period is 24 years and 25 years for the respective scenario. The scenario 'with fare' shows comparatively better results than without fare scenario. However, the actual willingness to pay for the user is still debatable. This is discussed in the discussion section of the report.

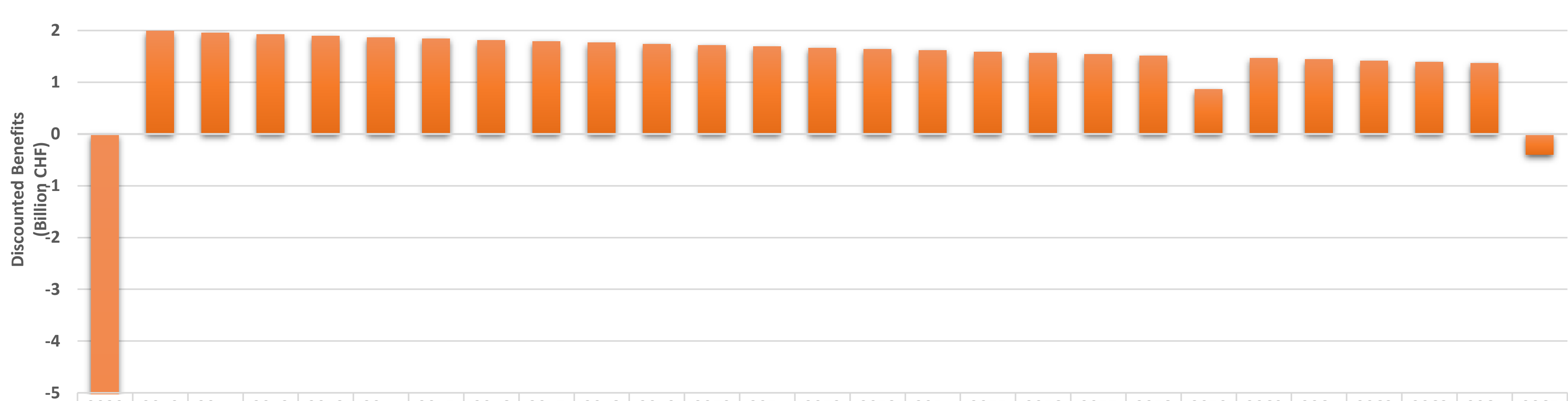
The costs and benefits mentioned in Table 4-2 are explained in more detail below:

4.4.1 Infrastructure cost

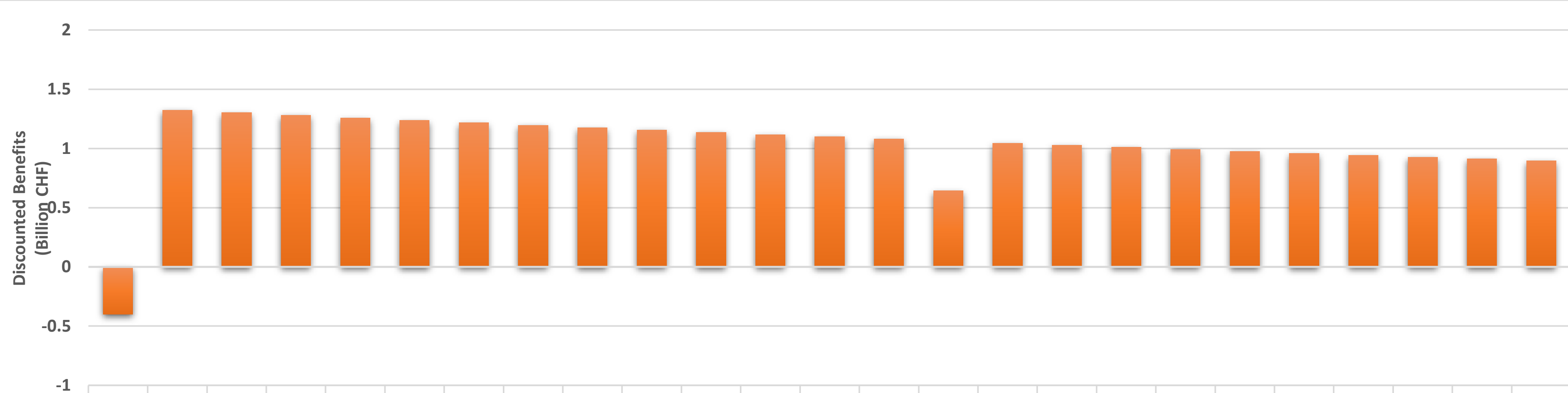
The infrastructure costs per unit are described in detail in chapter 3 of the document. Also, the output of the network generation algorithm gives the cost of the network for construction. However, the cost considered for the network generation algorithm is average annual cost and after the route design and frequency setting, the unused links need to be removed as well. This leads to a re-calculation of the infrastructure cost. Figure 4-11 shows the network after the removal of unused links. This network has a total length of 1026.418 km.

As mentioned in section 3.2.1, the total number of stations is 12. However, from the network structure, Bern and Zurich are hubs of the network i.e. being junctions of three or more lines. Thus, the cost of these stations is multiplied by a factor of 1.5 more than the estimated per station cost. For the rest of the stations, the estimated cost has been assumed.

This leads to a total cost of 51.32BCHF. This does not include the cost of vehicles. This will also remain the same for both cases.

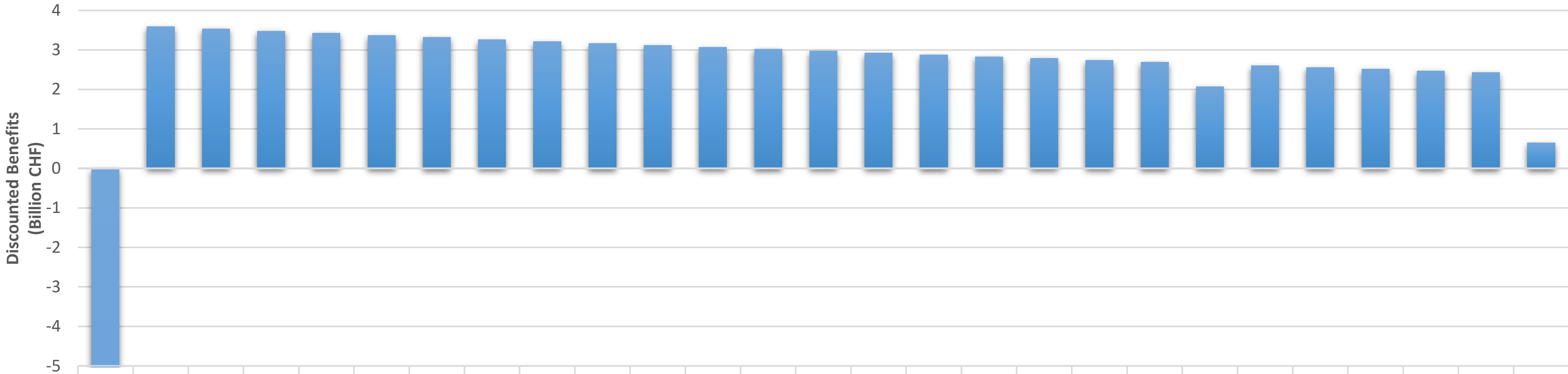


	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065
Years	-51.6	1.99	1.957	1.926	1.896	1.868	1.84	1.814	1.789	1.764	1.739	1.714	1.689	1.665	1.64	1.614	1.589	1.564	1.539	1.514	0.866	1.465	1.441	1.417	1.393	1.37	-0.4

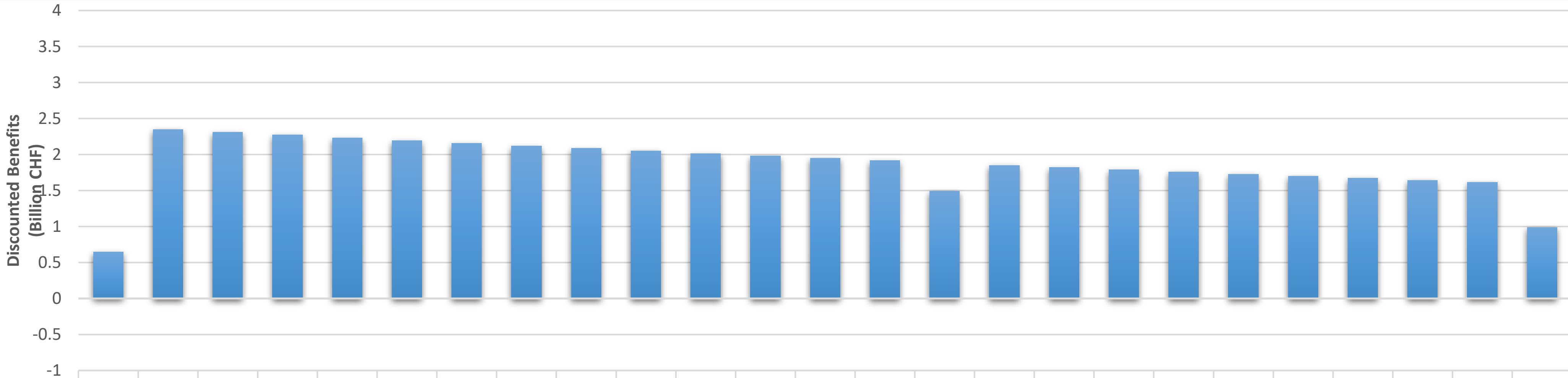


	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089
Years	-0.399	1.3241	1.3019	1.28	1.2585	1.2373	1.2165	1.1961	1.1759	1.1562	1.1367	1.1176	1.0988	1.0803	0.6424	1.0443	1.0267	1.0094	0.9925	0.9758	0.9594	0.9432	0.9273	0.9117	0.8964

Figure 4-14 Discounted net benefits:' without fare' Scenario



	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065
Years	-51.5	3.595	3.536	3.479	3.424	3.37	3.318	3.267	3.216	3.167	3.118	3.069	3.021	2.973	2.925	2.877	2.83	2.784	2.737	2.692	2.068	2.602	2.559	2.515	2.473	2.431	0.645



	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089
Years	0.645	2.35	2.31	2.271	2.232	2.195	2.157	2.121	2.085	2.05	2.015	1.981	1.947	1.915	1.493	1.85	1.819	1.788	1.758	1.728	1.699	1.67	1.642	1.614	0.986

Figure 4-15 Discounted Net Benefits: 'with fare' Scenario

4.4.1.1 Vehicle Cost

The number of vehicles required is calculated based on the cycle time of each line and headway per direction. The headways are calculated based on the frequency shown in Figure 4-11. Table 4-3 shows the number of vehicles required for each line along with cycle time and headway. 20 minutes[19] is added in the cycle time as the turnaround time. One extra vehicle is also added for each line in each direction, for the breakdown and other purposes. The vehicles are rounded off on the higher side. Line-3 shows a higher number of vehicles required since the cycle time is high, and the headway is very low.

Table 4-3 Number of vehicles required

Line	Cycle Time	'without fare' Scenario			'with fare' Scenario		
		Headway		No. of Vehicles	Headway		Number of Vehicles
		Up	Down		Up	Down	
1	14 mins 45s	15 mins	30 mins	3	20 mins	30 mins	3
2	26mins 5s	5 mins 30s	6 mins	11	6min 40s	8 mins	8
3	50 mins 55s	5 mins	2 mins	40	6min 20s	2 mins 20s	28

This results in a total number of vehicles required to be 60 and 45 for 'without fare' and 'with fare' scenario. Considering the 4.5 MCHF per vehicle cost, this will lead to 270MCHF and 202.5MCHF in the respective cases.

This leads to a total initial infrastructure investment cost of 51.59BCHF and 51.52BCHF for 'without fare' and 'with fare' cases respectively. This includes the cost of land and design planning.

4.4.2 Maintenance cost

After the initial infrastructure cost, the maintenance cost is considered the same as is explained in section 3.1.2. This consideration is taken on the basis of the average annual cost. Per year maintenance cost for track part is 55.62MCHF and 10.06MCHF for the station part. The cost for vehicle maintenance annually will be 1.62MCHF for 'without fare' scenario and 1.22MCHF 'with fare' scenario. This leads to a total of 2.16 BCHF and 2.14 MCHF of maintenance cost for the 'without fare' and 'with fare' scenario respectively over the analysis period.

4.4.3 Replacement cost

During the analysis period, propulsion system, vacuum pumps and vehicles will be required to be replaced twice, while the solar panels will be required to replace once[20]. This will lead to the addition of 2625.11MCHF for infrastructure-related elements; and for vehicles 286.853MCHF and 215.140MCH for 'without fare' and 'with fare' scenarios, respectively. This results in a total of 2911.96 MCHF and 2840.25MCHF of the replacement cost.

4.4.4 Operational cost

The operational cost has two considerations in terms of Hyperloop infrastructure, namely the stations and the vehicles. The operational cost for 12 stations would be

[19] 10 minutes on each end for cleaning and break for the staff (layover/ turn around).
[20] Age as per the table Table 3-3

206.92 MCHF annually. This will lead to 6.632 BCHF over the analysis period. The vehicle operational cost has been divided into two parts i.e. staff cost and energy cost. The staff cost is directly proportional to a number of vehicles, while the energy cost is proportional to travelled seat-km. The staff cost will be 7.11BCHF and 5.33BCHF annually for the 'without fare' and 'with fare' scenario respectively. This is calculated based on the number of vehicles mentioned in the sub-section4.4.1.1 and per vehicle staff cost mentioned in Table 3-3.

To calculate the energy cost, seat-km operated is required. Based on the frequency mentioned in Figure 4-11, the peak hour seat-km will be 16,954.786 seat-km and 13,677.736 seat-km for 'without fare' and 'with fare' case respectively. The peak hour model consists of 10% of the public transport daily demand (ARE, 2016). Assuming the same proportion for the Hyperloop seat-km, this will turn into 42.56Mseat-km and 34.33Mseat-km annually for 'without fare' and 'with fare' respectively. Based on the operational cost mentioned in Table 3-3, the total vehicle operational cost over the analysis period will be 16.55MCHF and 13.35MCHF for 'without fare' and 'with fare' case respectively.

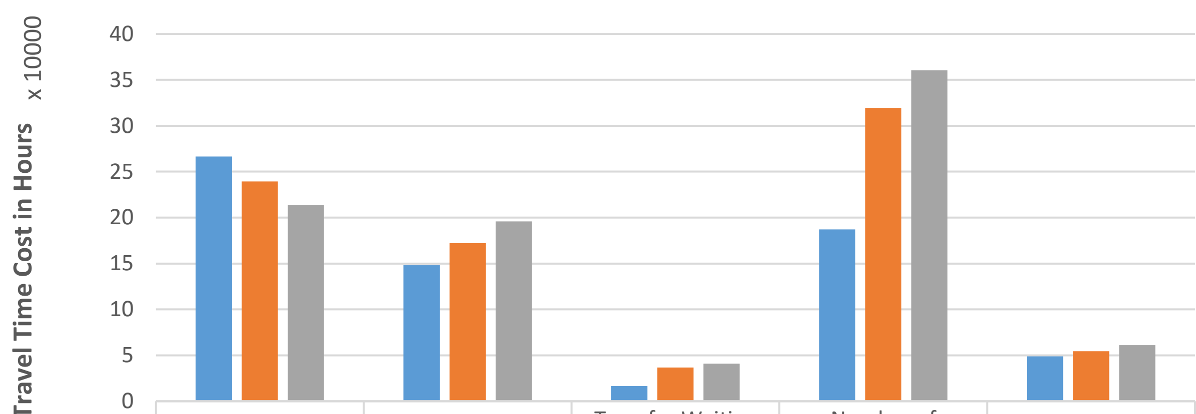
Thus, the total operational cost over the analysis period turns out to be 6.88BCHF and 6.82BCHF for 'without fare' and 'with fare' cases respectively. This also considers the population growth of 0.26% every year.

4.4.5 Travel time savings

Figure 4-16 shows the travel time results of peak assignment in the form of costs. From the figure, it can be observed that the travel times components of public transport show increase in the Hyperloop cases. This is because of the higher demand than the base case. In a similar way, the car networks show a reduction in total travel time, since lesser demand has reduced the congestion on the roads and also the demand is reduced as well compared to the base case.

The values of 'without fare' and 'with fare' cases are subtracted, from the base case from Figure 4-16 to calculate the travel time savings. These values are for peak hour. Therefore, they are converted to daily and annual numbers. As mentioned before, the car network captures 7.2% demand in peak hour of the daily demand, while PT network 10.0% (ARE, 2014). These ratios are applied to convert the values in daily travel time savings. Subsequently, to convert into annual values, 251 working days are considered as mentioned before.

Once the annual travel time savings are projected, the unit cost of the respective travel time component from section 3.2.2.3 is multiplied to convert the travel time savings in monetary values. This results in annual travel time savings of 992.49MCHF and 114.98MCHF for 'without fare' case and 'with fare' case respectively.



	Car Travel Time	In Vehicle Time	Transfer Waiting Time	Number of Transfers (No)	Access Time
Base Case	266451	148130	16440	187178	48785
Fare Case	239521	172285	36728	319440	54608
HL Case	213970	195832	40842	360677	61218

Travel Time Component

Figure 4-16 Travel time cost for peak hour in 2040

These annual values are compounded with the population growth factor of 0.26%[21] yearly up to 2089. This leads to total travel time savings over the analysis period 3.89BCHF and 33.57 BCHF for 'without fare' and 'with fare' cases respectively.

The travel time savings in 'with fare' case is significantly lower, compared to without fare case. This is mainly because of Access time. With fair case shows, 2.5 access time savings compared to without fare case, this has led to the higher difference in the cost value of access time savings as well because of the higher unit value of access time savings.

4.4.6 Fare revenue

The revenue is calculated based on the pass-km for Hyperloop. NPVM considers the cost of 0.20CHF/km (2010 rates) for PT. For without fare case, the same i.e. 0.36CHF/km (2040 rates) is considered, while for the fare case 0.50CHF/km (2040 rates) is considered. The pass-km can be directly extracted from the Visum assignment results. The assignment shows 2,386,870 pass-km and 2,296,132 pass-km for the Hyperloop system for 'without fare' and 'with fare' cases respectively. Similar to the previous subsection these values are projected for annual values and aforementioned costs are applied. This leads to revenue of 2,156.78 MCHF and 2,881.65 MCHF annually. It can be noted that these numbers are significantly higher than the annual total operational cost.

Similar to travel time savings, these numbers are discounted for the analysis period with 2% and population growth rate of 0.26% is also applied to compound annually. This results in 72.95BCHF and 97.46BCHF revenue for 'without fare' and 'with fare' cases respectively. The value of 'with fare' case is higher since the value of fare itself is significantly higher in the latter case. However, here it is required to mention that all the public transport modes observed an increase in the pass-km except long-distance

[21] https://www.bfs.admin.ch/bfs/en/home/statistics/population/population-projections/national-projections.html

trains. The long haul-double decker trains observed the loss of 33.49% and 38.52% loss of pass-km in 'without fare' and 'with fare' cases respectively.

After describing the CBA, the following section explains the results of the sensitivity analysis.

4.5 Sensitivity analysis

The section explains the sensitivity analysis performed for the network design process. This analysis is performed based on the Cost, VoT and Discount rate criteria. These criteria are selected based on the Swiss CBA norms. However, the norms also suggest demand as a criterion, but a due limitation of actual demand estimation, this criterion is not considered. To some extent, the scenario of 'with fare' also gives an indication of the network changes due to change in the demand. The study evaluates each phase of the network design for the sensitivity i.e. network generation, route design and CBA in 'without fare' scenario.

Considering the above-mentioned criteria for sensitivity, the discount rate is effective only in the cost-benefit analysis part, while the changes in costs and VoT are effective in all the phases. The cost considers all the cost from the supply side i.e. infrastructure, maintenance & operational cost. Given that, reduction in cost improves the B/C ratio only. This is less interesting compared to an increase in the cost. Therefore, an increase in the cost is only considered for the analysis. For the VoT, increase and decrease, both are considered for all the components of the travel time as per the Swiss CBA norms (Association Suisse des Professionnels, 2006).

As Table 4-4 shows, for the cost, four criteria are selected based on increase side at the 10% interval each, while for the VoT four criteria, with 10% of interval on each increase and decrease sides. For the discount rate, the norms suggest performing analysis with the value above 3%. This leads 50% minimum increase in the discount rate. These sensitivities are explained network design phase-wise in detail in the following subsections.

Similar to a traditional swiss public transit network, without fare scenario is considered for the sensitivity analysis.

Table 4-4 Sensitivity criteria

Criteria	**Change in Value**				
Cost	-	+10%	+20%	+30%	+40%
VoT	-20%	-10%	-	+10%	+20%
Discount Rate	-	+50%	+60%	+70%	+80%

4.5.1 Sensitivity in network generation

From the results, it is realised that both the approaches generate the same networks as far as the minimum spanning tree network has a B/C ratio above one. With each of the cost increase of 10%, one bi-directional link is reduced from the network. This leads to networks with 15(Figure 4-17), 14(Figure 4-18), 13(Figure 4-19), 12(Figure 4-20) number of links 10% higher cost. With a 50% higher cost case both the algorithm develops a different solution. However, that case is not considered as a part of this analysis. This will develop a lot of routes and will lead to higher operational cost for the link deletion algorithm.

With 10% variation in the VoT, the networks do not show any variations in terms of network structure and number of links. However, with 20% variation in the VoT the network shows a difference in the structure. The network with 20% reduction in the VoT shows 15 number of links (Figure 4-18) (same network structure as 10% increase in the cost), while 17 number of links in case of 20% increase in the VoT (Figure 4-21). The increase in the VoT leads to increased benefits of the network and higher benefits would allow more feasible links. In all the cases, the link swapping and link deletion algorithm make provides a solution with a B/C ratio above 1.

After network generation, the following subsection explains route design and frequency setting.

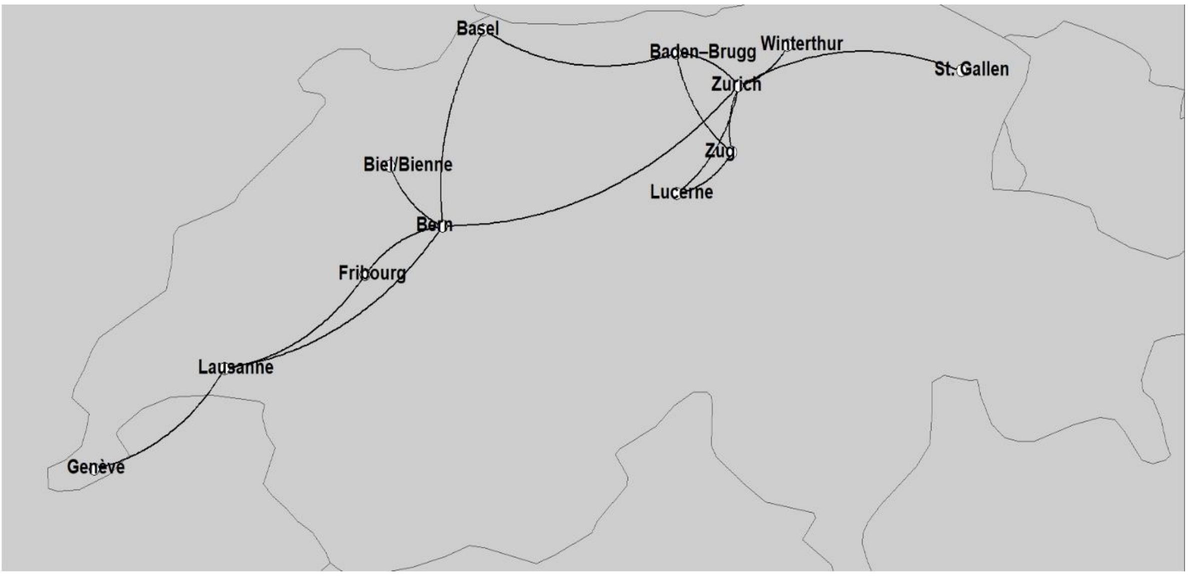


Figure 4-17 Network with cost +10%

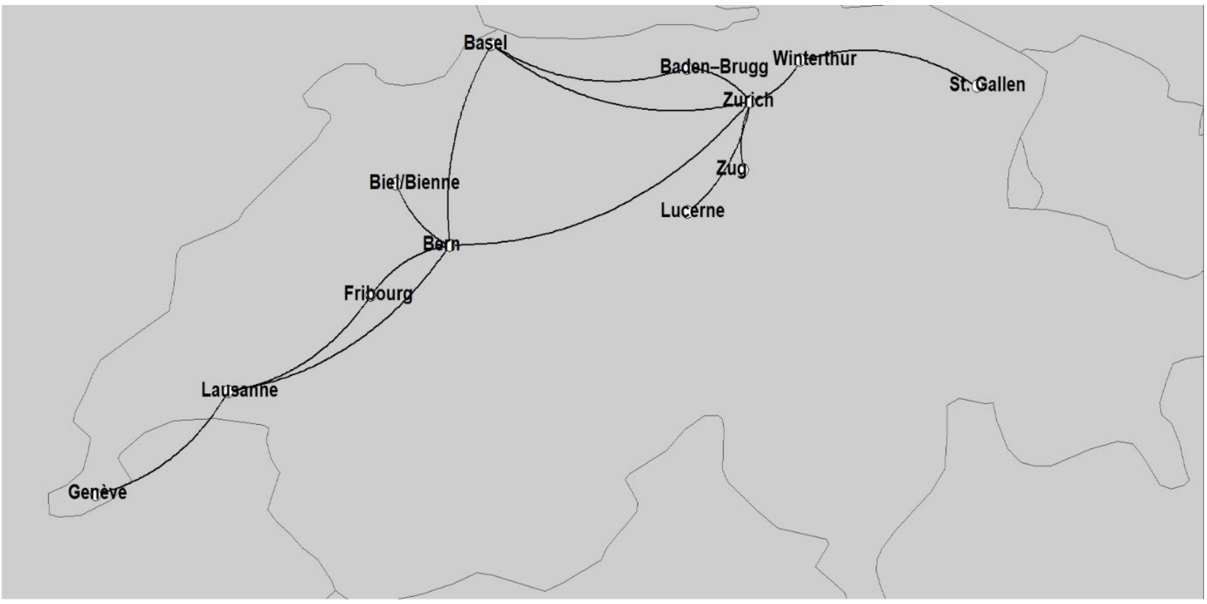


Figure 4-18 Network with cost +20% and VoT -20%

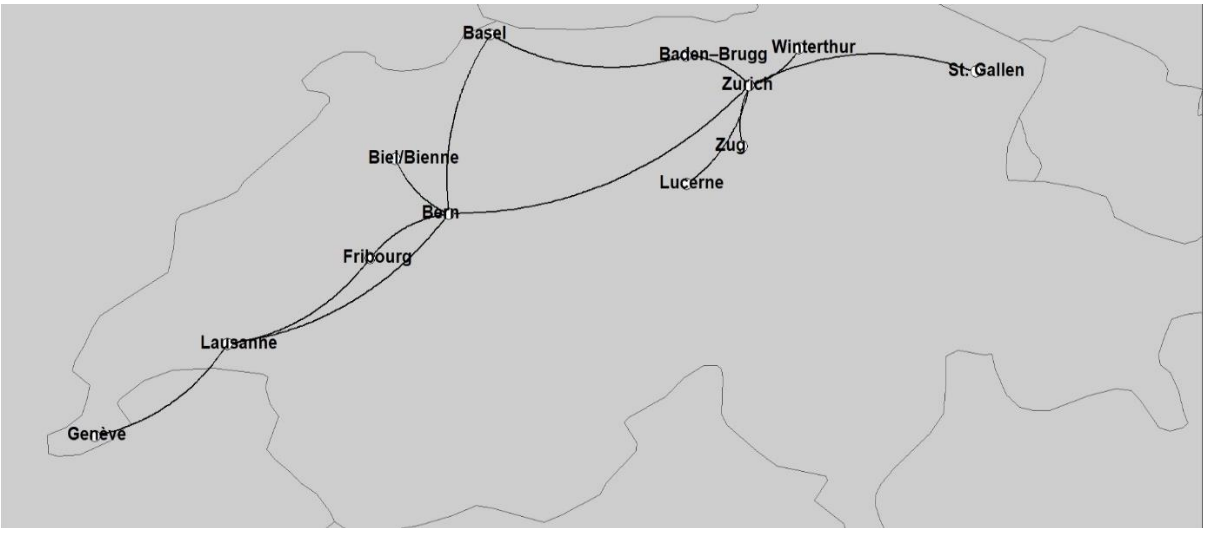


Figure 4-19 Network with cost +30%

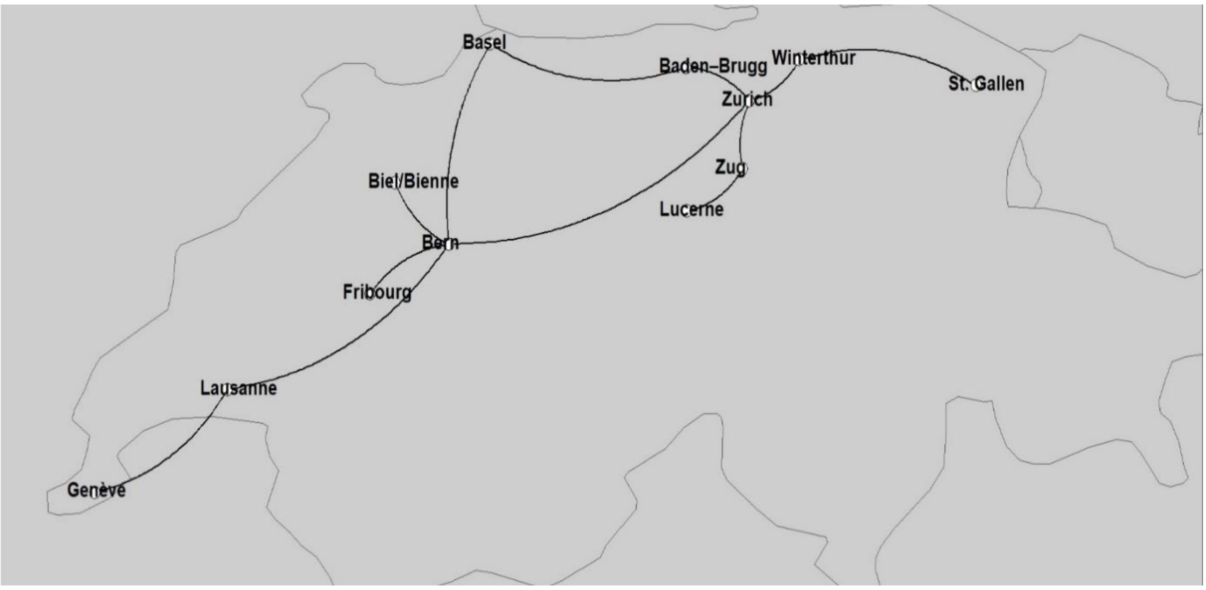


Figure 4-20 Network with Cost 40%

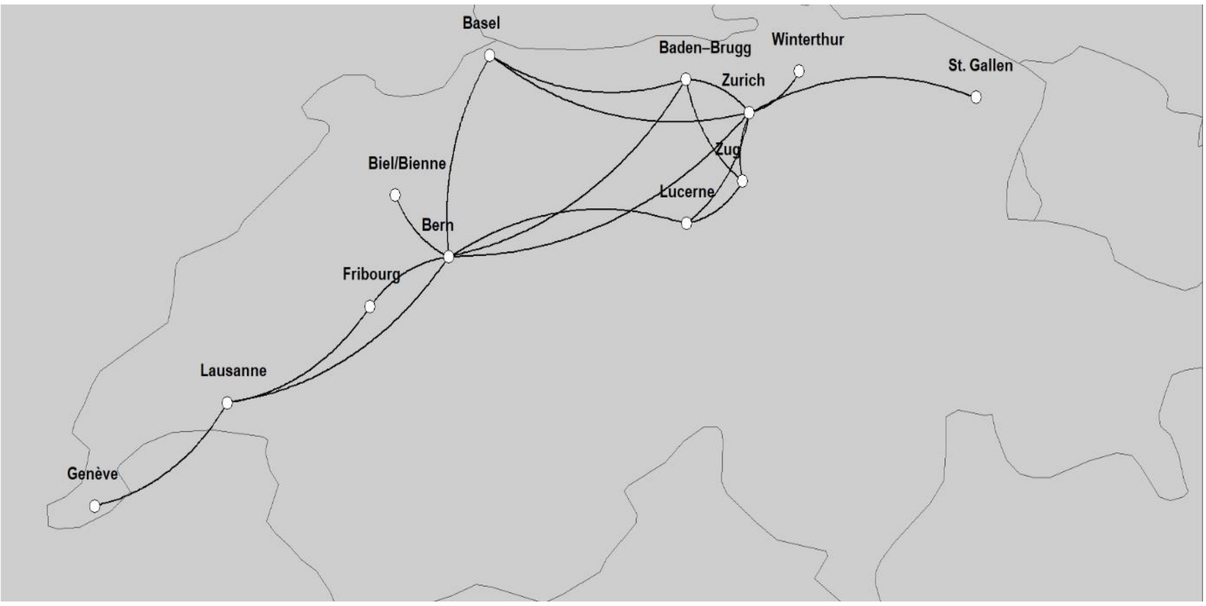


Figure 4-21 Network with VoT +20%

4.5.2 Sensitivity in routes

The change in the network structure also leads to a different set of routes. Considering the adapted approach for the route design, the networks do not show much variation. The routes generated can be categorized into three different types. This list is shown in Table 4-5 are finalized routes for different network structure with calculated frequency and number of vehicles required based on the cycle time of each line. These routes, as per the categories and frequencies are shown in the table.

Table 4-5 Sensitivity in routes

Type	Line	Stations	Frequency		No of Vehicles
			Up	Down	
1	1	St. Gallen, Zurich	3	2	60
	2	Winterthur, Zurich, Bern, Biel/Bienne	11	10	
	3	Lucerne, Zug, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève	12	32	
2	1	Lucerne, Zurich	2	2	58
	2	Zug, Zurich, Bern, Biel/Bienne	9	8	
	3	St. Gallen, Winterthur, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève	14	28	
3	1	Lucerne, Zug, Zurich, Bern, Biel/Bienne	13	12	51
	2	St. Gallen, Winterthur, Zurich, Baden–Brugg, Basel, Bern Fribourg, Lausanne, Genève	17	33	

The type 1 and 2 generated 8 different scenarios with routes, while type three developed 4 different scenarios of the routes. Type 1 routes are the same as the routes developed for the actual case. Type 2 routes are generated because Zug and Lucerne are not connected, while Winterthur and St. Gallen are connected. Type 3 routes have only two lines. This is because of fewer links in the network. This also leads to a smaller number of transfers overall Hyperloop networkwide. These route types related to different network cases are shown in Table 4-6. To define the frequency and number of vehicles required, a similar approach is adopted as described in the previous section.

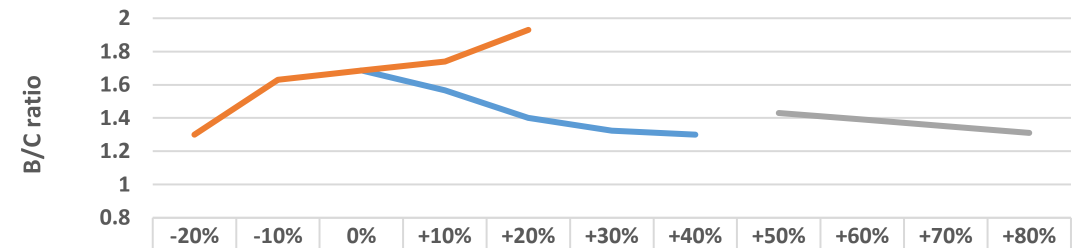
After identifying routes, frequencies and required number of vehicles, similar to previous section assignment are performed with all the types of routes with an existing network. The results of the assignment are directly showed with the B/C ratio.

Table 4-6 Route types with networks generated (con: Table 4-5)

			1	2	3
1	Cost	+10%	X		
2		+20%		X	
3		+30%		X	
4		+40%			X
5	VoT	-20%			X
6		-10%	X		
7		+10%	X		
8		+20%		X	

4.5.3 Sensitivity in cost-benefit analysis

After generating routes and frequencies, the B/C ratio needs to be re-calculated. In this stage of the analysis, the discount rate sensitivity case is also included.



	-20%	-10%	0%	+10%	+20%	+30%	+40%	+50%	+60%	+70%	+80%
Cost			1.69	1.57	1.40	1.32	1.30				
VoT	1.30	1.63	1.69	1.74	1.93						
Discount Rate								1.43	1.39	1.35	1.31

Change in the Value

Figure 4-22 B/C ratio vs Change in sensitivity criteria

Figure 4-22 shows the results from the sensitivity analysis. From the figure, it can be overserved that for all the cases, the B/C ratio remains above one. This is mainly because all the networks generated have initial B/C ratio above 1.

The discount rate shows a linear relationship with the B/C ratio. With every increase of 10% in the discount rate 0.04 reduction is noted in the B/C ratio. The minimum value of the B/C ratio turns out to be 1.31 in the case of discount rate with 80%. The purpose of the sensitivity in the discount rate is to capture the economical variations especially inflation. However, it should be noted that in the current analysis, the prices projected for the 2040 year are not changed. The values after the year 2040 up to analysis period only affected.

For the cost, the small increase led to a higher reduction in the B/C ratio compared to the discount rate. Figure 4-22 shows a sharp decrease in the B/C ratio at 20% increase in the cost. This is because of changes in the routes of the networks. With a 40% increase in the cost less reduction in B/C ratio is observed since this network is covered with a smaller number of routes. Also, the travel time savings increases with a reduction in a number of transfers.

Changes in VoT with 10% variation shows an almost linear relationship with the B/C ratio, as no changes in the networks are observed. With both extreme cases of VoT, the B/C ratio shows large variations. With a 20% reduction in VoT the B/C ratio drops to 1.30 and with 20% increase it reaches to 1.93.

To summarize, the discount rate shows a linear relationship with the B/C ratio, while cost and VoT shows linear until changes in routes. The change in the routes shows significant changes in the B/C ratio since it changes travel time savings, the number of vehicles required, and operational costs.

5 Conclusion & limitations

The current chapter of the document summarizes the key findings, limitations and future research. The key findings are described by answering the sub-research questions leading to answering the main research question. The subsequent section describes the limitations of the study and at the end, perspective for the future research is given.

5.1 Key findings

As mentioned before, the section describes the findings by answering the sub-research questions and the main research question. These findings are explained in a generalized manner as well as at the case-specific level. The case-specific answers may change according to the conditions of the respective case. The sub-research questions one and two focus on generalized findings, while sub-research questions three, four, five and six describe case-specific findings as well.

1. ***What are the inputs required for the network design of a Hyperloop system?***

   For the approaches of network design adopted in the current study, the inputs are (i) unit costs of infrastructure, operations and user; (ii) the demand for the network with existing travel times and (iii) the set of nodes (stations). These inputs are prepared either from the secondary data collected or from the available literature. It is observed that the network structure is highly correlated with the given inputs, especially costs and demand. The major assumption pertaining to the input of the demand and nodes is that they are considered fixed throughout the designing process. The total costs of the network vary with the network structure. However, these total costs do not capture the additional expenses incurred due to a change in the alignment of lines (such as curvature) and other critical geographical factors. The total demand of all the networks remains fixed throughout the design process. This is because induced demand is not considered in this research. The network structure is highly correlated with the input unit infrastructure & user cost (VoT), and demand. Rather than considering the speed of the mode (Hyperloop), seating capacity of a vehicle, and headway as design parameters, they can also be considered as variable inputs for the developed design process. This allows room for variations according to the design requirements of a study.

2. ***What are the methods to design/optimise transit networks such as Hyperloop?***

   From the literature, mainly four types of designing and optimising methods are identified. These methods are namely Conventional, Mathematical Programming, Heuristics and Meta-Heuristics. These methods have their own advantages and shortcomings mainly in-terms of computational time, quality of results and complexity of implementation. After comparing these characteristics, the current research is performed based on heuristic methods from the author’s perspective. The application of the methods can largely be categorised in two phases i.e. defining network structures (network generation) and designing routes.

The methods adopted for network generation algorithm namely link swapping and link deletion, are modified from the method of Bell et al. (2019). Both the methods generate the same outputs, provided the minimum spanning tree network has a B/C ratio greater than one. On the contrary, when the minimum spanning tree network has a B/C ratio less than one, both approaches generate different outputs. In the former case which is relevant to the current study, both the algorithm develops an output of heuristic nature. They identify the feasible set of links to design the routes.

The method for route design develops a set of candidate routes and subsequently looks for a feasible solution within the candidate set. The method is based on the algorithm developed by Mandl C. E. (1980). This output is also heuristic of its nature since optimisation takes place only within the candidate set of routes. The candidate set of routes is developed by identifying the longest shortest path on the feasible network. Subsequently, these routes are optimised based on the number of transfers i.e. user cost.

3. ***What is the feasible set of links in a Hyperloop network with respect to benefit to cost (B/C) ratio?***

This research question is answered via the output of the network generation algorithms. The output of each algorithm generates a set of links. These sets of links are generated by making sure that the B/C ratio of the network remains above one. However, here the B/C ratio consists of infrastructure cost and travel time savings (in-vehicle time) only. The set of links generated by the algorithms are such that any other non-chosen links will not have higher flow than selected links if they are added to the network. However, the generated set of links may be redundant in the network. This means that the B/C ratio is not maximum for the network for the considered costs.

For the current case of Switzerland, two scenarios are analysed: (i) ‘without fare’ scenario i.e. Hyperloop being part of the national subscription along with with rest of the PT network (ii)’with fare’ scenario i.e. a separate fare pricing system for the Hyperloop service. For the chosen 12 input nodes, 16 feasible bi-directional links for ‘without fare scenario’ and 15 feasible bi-directional links for ‘with fare scenario’ are identified. The ‘with fare scenario’ has less a link relatively since the demand is reduced.

4. ***Which is the optimal set of routes for the Hyperloop network generated in the previous sub-research question? What are the frequencies and number of vehicles required for the respective lines?***

On the generated network from the previous sub-research question, the lines are identified for a set of routes for both the cases. These lines are selected based on the longest shortest path of the networks generated. Once every node is covered by at least one line, no further lines are identified. Once the lines are defined, optimisation takes place based on the number of transfers. To optimise the number of transfers, different combinations of lines are generated by swapping the portions of the lines from the transfer node. These combinations can be in total 2^n, where n is the number of lines identified. The algorithm partially lowers the cost of operation by selecting a minimum number of lines. Subsequently, it optimises the user cost based on the number of transfers.

In the current swiss case, three lines were identified in both scenarios – ‘without fare’ and ‘with fare’. These three lines led to the generation of eight different combinations to optimise the set of routes based on the number of transfers. Since both the networks had a similar structure of the network, they resulted in the same set of routes.

The frequencies are defined based on the maximum load of a link. This approach of defining frequencies might have generated higher empty pass-km as frequencies are not optimised. Out of both the scenarios, the maximum and minimum determined frequency of 32 and 2 is found per hour. The lines with a minimum frequency of two depict that it is underutilisation. Based on the frequencies and cycle times of each line the number of vehicles required is identified. This turns out to be 60 nos. and 45 nos. for ‘without fare’ and ‘with fare’ case respectively.

5. ***What is the B/C ratio of the Hyperloop network generated in previous sub-research question?***

This sub-research question is difficult to answer in a generalised manner as B/C ratios are always specific to the case and scenario under consideration. The results from the analysis show the B/C ratio of 1.69 and 1.61 for the ‘without fare’ and ‘with fare’ cases respectively. Though the fare revenue increases for the ’with fare’ case, the travel time savings and demand both decreased significantly for the same. For the ‘without fare’ scenario, the discounted internal rate of return turns out to be 3.24% with the discounted payback period of 24 years. For the ‘with fare’ scenario the discounted internal rate of return turns out to be 2.90% with the discounted payback period of 25 years. However, in terms of economic B/C ratio i.e. considering only monetary parameters (without travel time savings), these ratios turn out to be 1.15 and 1.53 for the ‘without fare’ and ‘with fare’ scenario respectively. In this situation, though the demand is lower in the ‘with fare scenario’, the revenue generated from the fare is significantly higher because of a higher value of fare per km (the fare for the Hyperloop is 40% higher than base fare of the public transport per km) itself.

6. ***To what extent is the B/C ratio of the Hyperloop network sensitive to its design inputs?***

The sensitivity analysis performed on the Hyperloop network shows expected results. Mainly three criteria are considered this for analysis, namely the discount rate, VoT and costs. The discount rate shows a linear relation with the B/C ratio. The increase in the discount rate leads to a decrease in the B/C ratio.

The network generation algorithm generates more links than required to cover the routes for the case. Because of this, two observations are made – (i) with the change in the network structure, different set of routes are generated (ii) with the change in network structure, the routes remain the same.

The cost and VoT also show a linear relation with the B/C ratio. The cost is inversely proportional to the B/C ratio, while VoT is directly proportional to the B/C ratio. It is observed that the gradient of the B/C vs Cost and B/C ratio vs VoT changes as routes are changed in the network.

In the current case of Switzerland, the sensitivity analysis is performed on ‘without fare’ scenario. The analysis of the discount rate between the interval of +50% to +80% shows ratio linear decrease in the B/C ratio from 1.43 to 1.31. In the B/C ratio vs cost curve, the B/C ratio ranges from 1.69 to 1.30 with the cost of +0% to +40%. Similarly, the B/C ratio changes from 1.30 to 1.93 for the interval of -20% to +20% in VoT. All of the three criteria are analysed with every 10% interval.

Thus, answering the sub-research question leads to the answer to the main research question. The main research question is answered by explaining a generalised solution followed by key findings realised from the case of Switzerland.

“How can a Hyperloop network be designed based upon the determinants of the cost-benefit analysis?”

The determinants of the cost and benefit analysis consist of (i) infrastructure cost, (ii) maintenance cost, (iii) operational cost, (iv) replacement cost (v) travel time savings and (vi) fare revenue. It is difficult to incorporate all the determinants in each phase of the network design process. This is because the method adopted in this study is sequential. In this case, the network generation phase includes travel time savings (in-vehicle time savings) and infrastructure cost. In the route design phase, the routes are generated in a way that a minimum number of lines are required to cover the network. This minimises the operational cost to some extent. Subsequently, the number of transfers is minimised on the candidate set of lines, which in turn leads to minimisation of the user cost. On the other hand, the frequency setting does not involve optimisation. This may lead to a higher number of vehicles required. The overall procedure is aimed at generating a network that has a B/C ratio above one. In case, it is unable to do so, a maximum possible B/C ratio less than one is attained.

The aforementioned procedure can give an indication of how determinants of costs and benefits can be involved in the network design process. Indeed, the considered costs and benefits for defining the network structure and routes are not complete. However, these can be improved by adding more costs and benefits parameters further, especially in terms of externalities like environment emissions, noise, accident cost and many more. This will also improve the design towards the viability of the networks.

For the case of Switzerland, two scenarios are analysed: (i) ‘without fare’ scenario i.e. Hyperloop being part of the national subscription along with with rest of the PT network (ii)’with fare’ scenario i.e. a separate fare pricing system for the Hyperloop service. With beta parameters of the existing public transport network, the Hyperloop could make the modal-shift of 11% and 6.5% of the car demand in ‘without fare’ and ‘with fare case’ respectively. For the demand estimated, the generated networks and designed route could reduce the total travel time of the PT network significantly. This led to a B/C ratio of 1.69 and 1.61 for the ‘without fare’ and ‘with fare’ cases respectively. The higher B/C ratio of without fare scenario is because it could attract more demand from the car network. However, here significant loss of pass-km is also found in the long-haul trains. The performed CBA included determinant costs and benefit only. For both the scenarios, it is found that the annual operational cost is covered by annual fare revenue for all the years. This is an important observation for a public transport system.

5.2 Limitations

The current section of the document discusses the limitation of the study in each phase and recommends further improvements for the same. The section first describes the methodological limitations, followed by input related limitations and lastly, limitations due to the assumptions made during analysis. The methodological limitations discuss the global assumptions, while the analysis limitations discuss the case-specific assumptions. The section of input limitations is discussed by comparing global and case-specific assumptions.

5.2.1 Methodological limitations

The study adopted the fixed demand approach since the case study has a separate interface for network simulations and for the decision model of the demand estimation. This is mainly to reduce the overall computational time and to study the characteristics of the networks individually. The simulated networks in the case study are also divided further divided into car and PT network by NPVM. Combining these elements i.e. making demand iterative along with the changes in the network could give better results for the overall network design. This could be further extended by making routes iterative to network generation. The current sequential approach of route design also generated a limited number of candidate routes. This would turn results heuristic by nature. Combining the interface of network generation route design and simulation would improve the quality of the results.

The link swapping algorithm selects maximum direct demand nodes while adding links. On the removal side, both the algorithms remove links based on the minimum flows. These criteria were adopted for reducing the complexity of the algorithms. The addition and removal criteria can be further improved by considering the B/C ratio as an adding and removing criteria as well. Adapting these criteria along with the iterative demand could extend the network generation algorithm itself towards optimizing. This would also solve the issue of generating mono-centric networks mentioned in section 4.1.2.

The B/C ratio for the network generation could only consider the travel time savings on the basis of direct travel. This is mainly due to limited literature available for the other benefits and cost elements. For example. internalities like environment emissions, accident cost, noise, etc. Adding these components in the objective function itself could improve the design.

Given the size of the study area, the optimization on networks is performed considering the constraint of the connected network. This was also considered due to higher operational cost of stations. However, the possibility of disconnected networks still needs to be explored.

In the route design phase, the routes are optimized based on the number of transfers i.e. user cost. It could not capture the cost of the vehicles. However, considering the longest shortest path for the candidate routes, partially lower the operational cost (including vehicles required), but do not optimize. The frequencies are determined based on the maximum load on the link in peak hour. This could have overestimated the vehicles required and resulted in a higher cost for the same.

5.2.2 Input limitations

The major limitations of the study are due to the inputs. This includes mainly cost-related and demand related limitations.

The demand estimation for public transport network including Hyperloop is performed considering the same beta parameters as an existing public transport network. This is mainly due to the unavailability of the literature or data to estimate the values. This needs to improve by estimating the new values for beta parameters. In principle, adding Hyperloop to the public transport network will improve the attractiveness and VoT of the overall network. A detailed study needs to be performed for estimating these beta parameters. Similarly, the variable values for parking time and parking cost for the car network was not available. This increased the error in demand estimation. The demand estimation does not consider capacity constraints. However, this is more related to simulation and analysis. This will be discussed in further sub-section of simulation limitations.

NPVM considers the same fare for all the public transport mode. This is because all the public transport operators within Switzerland are obliged to provide service under this national subscription of General Abonnement. This makes it difficult to estimate the demand based on the different fare pricing for Hyperloop. To overcome this issue, the current study translates overhead fare price of Hyperloop into in-vehicle time. However, this conversion will not do justice to actual effects on demand due to different weights of variables.

The assumption that Hyperloop characteristics are similar to those of conventional public transport also needs to be verified. However, for the current research, some characteristics of the Hyperloop are based on the conventional scheduled services. The assumptions of speeds are based on the musk studies and limitation of the simulating software Visum. The Musk study estimates the speed of 1,220km/hr with 1G acceleration. These assumptions are reduced due to 500 km/hr & 1,000km/hr and 0.5G based on the distances (30km link length criteria) to make them more realistic values.

From the cost side, very limited literature is available to estimate the cost. However, estimation from these studies also varies in a large range. This is mainly due to uncertainty about the viability of materials to be used for the infrastructure. For e.g. study from Transpod performed cost estimation by assuming steel material for tubes, while musk estimation follows concrete for the same. The issue of cost is also relevant to vehicles because of different sizes being predicted for the Hyperloop. The other major cost consideration is related to operational cost. Only one study is performed evaluating the operational cost of Hyperloop, in which, the cost estimates are specific to the assumption related to specifications of the vehicles and infrastructure made in the study. Projecting the same estimates for the current study could have deviated the results. Since the operational cost has a large impact on the profitability of the projects, this needs to be improved primarily. This will also give the base for the fare pricing.

The cost from the countries is converted based on the purchasing power parity. This approach does not capture the actual market values. However, this approach also needs to consider the things which can be developed locally or need to be imported.

The assumption of access time for the Hyperloop stations is also optimistic in the current study. It is assumed that the access time for Hyperloop station will be similar to the main railway stations. This is mainly due to the assumption of mounting Hyperloop stations on existing railway stations and using Hyperloop for a daily commute. However, operating services at high speed of 1000km/hr might need some consideration of safety. This can result in increased access time. Mounting Hyperloop stations on existing stations would lead to questions of both space and design. The current study assumes the cost for land and design based on the percentage value of the investment specific to the infrastructural element. The assumption is also valid due to unavailability of such preliminary designs. Transpod study has given reliable assumptions for the Tube part of the infrastructure with preliminary designs. Similarly, other major elements can be investigated, which will lead to better estimates.

The other major missing element from the cost perspective is Switches on the stations. There is no description in the literature about switches except the Delft Hyperloop Study. The cost for the switches in the study is significantly over-estimated. This also needs a thorough investigation. Shifting from one tube to another will require switches. Apart from the cost of the same, time, speed and other characteristics also need investigation for the same. The other major consideration is about stopping time and headway. The musk study initially assumed six minutes of headway. This has been reduced by various studies. The most optimistic assumption projects the headway of the 20s[22]. Considering passenger (50 nos) in-out time and safety check for seat belts, this assumption does not justify these activities.

5.2.3 Assignment model and analysis limitations

The assignment for the Hyperloop network is performed in Visum 16.0.1-04 version. This process is done by adding designed Hyperloop network to existing PT network to analyze overall networkwide effects. However, there are some limitations to this approach. The major drawback is the capacity constraint. The NPVM assignment model does not consider the capacity constraints and assigns demand to the link via the shortest perceived journey times for respective OD pairs. The major drawback with this approach is that the Hyperloop would attract large demand from the existing public transport since the price is the same under GA subscriptions and the weights of transfers are not significantly higher compared to in-vehicle travel times. This has also shown that the flow on the Hyperloop links is over the capacity flow. This will make existing services lose a significant amount of pass-km. Also, the actual delay in the journey time cannot be measured.

Performing assignment under peak hour model also overestimates the resources required and the benefits. This is mainly because the results of the peak hour model are used to project the values for the analysis period. This needs to be verified by performing under a daily model.

[22] Informal sources via interview at Hardt Global.

The CBA performed in the study is not complete in itself, as many of the costs need to be added in the analysis as mentioned in the previous subsection. This includes externalities, maintenance and operational cost of other networks, etc. Since the demand has been reduced for the road networks in both the Hyperloop cases, this will reduce the maintenance cost for the roads and operating cost for the vehicles. This has not been covered. Similarly losing pass-km for PT will reduce maintenance and operational cost for the same.

The VoT from the Swiss CBA norms and NPVM does not match. The variation range is approximately 1.5 times to two folds. This is mainly because of applying different dataset for estimating these values in both the studies. Also, the number of trip purposes and travel time components are different in both the studies. However, for the current study, the values are considered based on NPVM, because the demand estimation was based on NPVM.

Station development, i.e. the development of retail spaces inside and around the stations, can reduce a large amount of initial investment. However, this can be only done after the preliminary designs. This is also related to assuming the two-fold costs for the major hubs. This assumption, also arbitrarily made, needs detailed investigation by comparing station cost around the world. This is also related to the cost assumptions made in the study, especially the infrastructure cost. The study only considers the cost estimates pertaining to Hyperloop in the literature. However, a comparison of similar elements from different systems could improve these cost estimates.

After describing the limitations and discussions of the study, the following subsection gives a recommendation for future research.

5.3 Future research

Though the previous section of discussion gives the indication of future improvements, the current section gives different approaches to the elements of this research. Since the Hyperloop system is at its development phase, a large number of future study recommendations can be drawn especially in the vehicle engineering part and civil engineering elements. Therefore, it is important to mention that the section only gives recommendation related to transport network design and modelling.

- An interesting study would be to estimate the beta paraments for Hyperloop similar to the Swissmetro study. However, no Hyperloop project has been realized so far, therefore a stated preference study would be interesting to estimate these values. Including air, passengers would also increase the larger societal benefit.
- Some of the studies estimate the capacity of 28 passengers and very short headway (approx. 1-2 mins). In this situation, designing on-demand service will be an interesting approach to investigate further.
- Possibility of implementing different meta-heuristic algorithms for large networks (e.g. European Hyperloop Network) can also give better insights about their performance. A priority should be given to non-implemented approaches like IACGA, migrating birds' optimization. This also includes a detailed evaluation of routes and frequency optimization.

- As mentioned in the previous section, preliminary designs of the different Hyperloop infrastructural elements will enhance the CBA for the Hyperloop system. This also includes defining the operational cost.
- In order to develop a thorough cost-benefit analysis of the Hyperloop system, deriving constants for externalities like environment emissions, noise, safety, accidents, etc would be an interesting study as well.
- Another interesting insight related to Hyperloop mode can be drawn from the sensitivity of fare to the demand and B/C ratio. Combining this with the feasibility of the business model i.e. private operator or public operator or both can give a better understanding of financial feasibility.

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7 Appendix

Appendix:1 Existing car demand of Switzerland

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	0	504	1	244	0	0	268	0	0	0	0
Fribourg	0	0	0	0	0	2752	28	0	0	0	507	3
Baden	1571	0	0	21	2178	4	3	189	827	0	0	0
Winterthur	2	0	18	0	321	4	0	2	2	30	0	0
Zurich	155	0	1021	179	0	47	6	40	41	17	0	0
Bern	0	466	2	3	81	0	175	56	128	0	28	2
Biel	0	7	3	0	15	311	0	7	28	0	1	0
Lucerne	296	0	109	2	67	42	5	0	58	0	0	0
Basel	0	0	477	1	34	72	12	22	0	0	0	0
St. Gallen	0	0	0	60	104	0	0	0	0	0	0	0
Lausanne	0	104	0	0	0	62	1	0	0	0	0	75
Genève	0	1	0	0	0	1	0	0	0	0	77	0

Appendix:2 Existing PT demand of Switerland

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	0	101	40	1352	2	0	682	2	0	0	0
Fribourg	1	0	38	1	41	1554	35	9	13	0	888	163
Baden	300	27	0	275	6394	523	44	204	1137	3	0	0
Winterthur	31	0	198	0	2615	161	6	26	44	181	1	0
Zurich	554	4	1946	908	0	817	51	243	572	343	13	0
Bern	2	503	117	69	1347	0	288	255	890	3	112	24
Biel	0	10	36	9	174	770	0	11	53	1	56	7
Lucerne	670	2	76	27	902	319	7	0	194	1	2	0
Basel	1	3	466	33	759	967	12	188	0	0	5	0
St. Gallen	1	0	2	162	770	8	0	2	1	0	0	0
Lausanne	0	279	2	4	111	1216	289	6	61	0	0	1107
Genève	0	79	0	0	4	126	10	1	1	0	761	0

Appendix:7-1 PT Demand including Hyperloop network 'without fare' scenario

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	0	101	40	1352	2	0	682	2	0	0	0
Fribourg	1	0	38	1	41	1554	35	9	13	0	888	163
Baden	300	27	0	275	6394	523	44	204	1137	3	0	0
Winterthur	31	0	198	0	2615	161	6	26	44	181	1	0
Zurich	554	4	1946	908	0	817	51	243	572	343	13	0
Bern	2	503	117	69	1347	0	288	255	890	3	112	24
Biel	0	10	36	9	174	770	0	11	53	1	56	7
Lucerne	670	2	76	27	902	319	7	0	194	1	2	0
Basel	1	3	466	33	759	967	12	188	0	0	5	0
St. Gallen	1	0	2	162	770	8	0	2	1	0	0	0
Lausanne	0	279	2	4	111	1216	289	6	61	0	0	1107
Genève	0	79	0	0	4	126	10	1	1	0	761	0

Appendix:7-2 PT Demand including Hyperloop Network 'with fare' scenario

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	0	171	41	1377	2	0	700	2	0	0	0
Fribourg	1	0	38	1	41	2286	47	9	13	0	1064	165
Baden	387	27	0	277	6350	644	45	223	1163	3	0	0
Winterthur	33	0	199	0	2590	176	6	28	45	190	1	0
Zurich	584	4	1932	905	0	923	53	269	598	351	13	0
Bern	2	578	117	70	1383	0	386	260	989	3	124	25
Biel	0	12	37	10	179	1020	0	13	76	1	56	7
Lucerne	709	2	97	28	947	356	9	0	191	1	2	0
Basel	1	3	472	33	780	1124	21	188	0	0	5	0
St. Gallen	1	0	2	177	821	9	0	2	1	0	0	0
Lausanne	0	310	2	4	111	1349	190	6	61	0	0	1100
Genève	0	80	0	0	4	138	10	1	1	0	765	0

Appendix:7-3 Car travel time existing network

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	95	36	44	27	78	80	24	67	78	131	161
Fribourg	93	0	79	100	90	24	41	80	75	132	44	78
Baden	36	78	0	33	25	62	64	46	42	72	114	145
Winterthur	45	102	33	0	25	83	85	52	62	38	138	168
Zurich	26	91	25	20	0	74	76	33	54	54	127	157
Bern	77	24	62	82	74	0	27	63	58	115	60	90
Biel	79	41	64	85	77	27	0	66	60	117	66	93
Lucerne	23	80	44	50	33	63	66	0	57	83	116	146
Basel	66	75	42	62	55	58	61	58	0	96	111	141
St. Gallen	79	132	72	39	55	115	117	83	96	0	168	198
Lausanne	129	44	114	136	126	60	66	116	111	168	0	42
Genève	160	78	145	166	157	90	93	146	141	198	42	0

Appendix:7-4 Existing travel time PT network

Name	Zug	Fribourg	Baden	Winterthur	Zurich	Bern	Biel	Lucerne	Basel	St. Gallen	Lausanne	Genève
Zug	0	121	59	62	28	94	107	26	99	118	166	199
Fribourg	122	0	97	122	87	31	65	89	93	179	49	87
Baden	57	97	0	50	18	70	82	75	62	106	141	174
Winterthur	56	119	50	0	17	94	105	81	93	48	164	197
Zurich	25	85	16	21	0	64	73	48	64	74	130	162
Bern	95	30	68	95	64	0	34	70	65	149	73	110
Biel	107	64	81	108	75	34	0	88	71	161	60	87
Lucerne	25	88	73	86	50	68	89	0	74	139	135	171
Basel	96	94	59	96	64	67	74	78	0	149	138	170
St. Gallen	116	171	104	49	75	146	157	137	146	0	216	249
Lausanne	166	48	140	166	129	73	61	135	135	219	0	37
Genève	199	86	173	200	162	110	87	170	167	252	36	0

Appendix 7-5 Results of link swapping: 'without fare' scenario

iteration	add_remove_link	Link	network_benefits	network_costs	network_bc_ratio
0	initial_mst	NA	1125053514	650575307.1	1.729320959
1	link_added	Zurich, Bern	1147391484	779446470.8	1.472059374
2	link_added	Bern, Basel	1151982219	869879681.7	1.324300639
3	link_added	Bern, Lausanne	1155547490	975100763.8	1.18505444
4	link_added	Zurich, Basel	1158216912	1074500949	1.077911483
5	link_added	Zurich, Lucerne	1163825946	1128811635	1.031018737
6	link_added	Zurich, St. Gallen	1165729626	1213001068	0.961029348
7	link_removed	Biel/Bienne, Basel	1164904414	1141830189	1.020208105
8	link_added	Baden–Brugg, Bern	1167394122	1259976773	0.926520351
9	link_removed	Winterthur, St. Gallen	1166324640	1193662330	0.977097635
10	link_added	Zug, Baden–Brugg	1167267019	1243445433	0.938736021
11	link_removed	Baden–Brugg, Bern	1164777310	1125298849	1.035082646
12	link_added	Baden–Brugg, Winterthur	1165963292	1167437772	0.998736995
13	link_removed	Baden–Brugg, Winterthur	1164777310	1125298849	1.035082646

Appendix 7-6 Results of link swapping: 'with fare' scenario

iteration	add_remove_link	link	network_benefits	network_costs	network_bc_ratio
0	initial_mst	NA	1059981273	650575307.1	1.629298
1	link_added	Zurich, Bern	1082932234	779446470.8	1.389361
2	link_added	Bern, Basel	1087470053	869879681.7	1.250138
3	link_added	Bern, Lausanne	1090982315	975100763.8	1.118841
4	link_added	Zurich, Basel	1093529674	1074500949	1.017709
5	link_added	Zurich, Lucerne	1099175707	1128811635	0.973746
6	link_removed	Biel/Bienne, Basel	1098539241	1057640756	1.03867
7	link_added	Zurich, St. Gallen	1100390484	1141830189	0.963708
8	link_removed	Winterthur, St. Gallen	1099400561	1075515746	1.022208
9	link_added	Baden–Brugg, Bern	1101869561	1193662330	0.9231
10	link_removed	Baden–Brugg, Bern	1099400561	1075515746	1.022208

Appendix 7-7 Results of link deletion:' with fare' scenario

iteration	remove_link	link	network_benefits	network_costs	network_bc_ratio
0	initial_fg	NA	1177955285	9386042806	0.125500737
1	keep_removing	Zug, Lausanne	1177955285	8510410971	0.138413443
2	keep_removing	Fribourg, St. Gallen	1177955240	7975384058	0.147698873
3	keep_removing	St. Gallen, Lausanne	1177955157	7664793782	0.153683868
4	keep_removing	Winterthur, Genève	1177954896	7338244460	0.160522711
5	keep_removing	Zug, Biel/Bienne	1177953893	7208714961	0.163406918
6	keep_removing	Lucerne, Genève	1177953300	6953348454	0.169408064
7	keep_removing	Biel/Bienne, St. Gallen	1177952584	6733341140	0.17494325

8	keep_removing	Zug, Fribourg	1177951009	6583518417	0.178924237
9	keep_removing	Zug, St. Gallen	1177949005	6489314963	0.181521318
10	keep_removing	Basel, Genève	1177948040	6241049828	0.18874197
11	keep_removing	Basel, St. Gallen	1177947083	6060231517	0.194373281
12	keep_removing	Fribourg, Winterthur	1177944281	5869499462	0.200689052
13	keep_removing	Baden–Brugg, Lausanne	1177942421	5646297857	0.208622083
14	keep_removing	Lucerne, St. Gallen	1177939162	5525176188	0.21319486
15	keep_removing	Zug, Basel	1177935116	5416097129	0.217487812
16	keep_removing	Zurich, Genève	1177931813	5115149416	0.230282973
17	keep_removing	Zug, Bern	1177926445	5000503847	0.235561552
18	keep_removing	Winterthur, Lausanne	1177922600	4741437720	0.248431524
19	keep_removing	Baden–Brugg, St. Gallen	1177919031	4633785166	0.25420234
20	keep_removing	Lucerne, Lausanne	1177912190	4444164097	0.265046961
21	keep_removing	Bern, St. Gallen	1177900781	4235693570	0.278089234
22	keep_removing	Fribourg, Basel	1177887924	4116035517	0.286170496
23	keep_removing	Winterthur, Biel/Bienne	1177872383	3956285378	0.297721795
24	keep_removing	Biel/Bienne, Genève	1177858116	3778350650	0.311738699
25	keep_removing	Fribourg, Lucerne	1177837246	3654359604	0.322310165
26	keep_removing	Biel/Bienne, Lucerne	1177765158	3544997217	0.332233027
27	keep_removing	Fribourg, Zurich	1177689350	3379582597	0.348471835
28	keep_removing	Winterthur, Lucerne	1177614445	3300346955	0.356815347
29	keep_removing	Fribourg, Baden–Brugg	1177505405	3145606734	0.374333318
30	keep_removing	Basel, Lausanne	1177454367	2963337054	0.397340682
31	keep_removing	Zug, Winterthur	1177297712	2910391508	0.404515237
32	keep_removing	Winterthur, Basel	1177236044	2795675227	0.421091847
33	keep_removing	Baden–Brugg, Biel/Bienne	1177072399	2676140723	0.439839501
34	keep_removing	Fribourg, Biel/Bienne	1176693539	2626127943	0.448071673
35	keep_removing	Zurich, Lausanne	1176598422	2392530243	0.491779958
36	keep_removing	Bern, Genève	1176316327	2219538952	0.529982286
37	keep_removing	Winterthur, Bern	1175979519	2065462110	0.569354196
38	keep_removing	Biel/Bienne, Basel	1175376001	1994291231	0.58937029
39	keep_removing	Biel/Bienne, Lausanne	1174668491	1883011926	0.623824244
40	keep_removing	Baden–Brugg, Lucerne	1174107819	1819222969	0.645389729
41	keep_removing	Zurich, Biel/Bienne	1173260203	1682586295	0.697295709
42	keep_removing	Winterthur, St. Gallen	1172188223	1616271852	0.725241995

43	keep_removing	Lucerne, Basel	1170626319	1511991356	0.774228182
44	keep_removing	Fribourg, Genève	1170615470	1375674529	0.850939263
45	keep_removing	Bern, Lucerne	1168453000	1285584356	0.908888627
46	keep_removing	Baden–Brugg, Winterthur	1167267019	1243445433	0.938736021
47	stop_removing_bca	Baden–Brugg, Bern	1164777310	1125298849	1.035082646

Appendix 7-8 Results of link deletion: 'with fare' scenario

iteration	**remove_link**	**link**	**network_benefits**	**network_costs**	**network_bc_ratio**
0	initial_fg	NA	1112792093	9386042806	0.118558
1	keep_removing	Zug, Lausanne	1112792093	8510410971	0.130757
2	keep_removing	Fribourg, St. Gallen	1112792048	7975384058	0.139528
3	keep_removing	St. Gallen, Lausanne	1112791965	7664793782	0.145182
4	keep_removing	Winterthur, Genève	1112791704	7338244460	0.151643
5	keep_removing	Zug, Biel/Bienne	1112791046	7208714961	0.154367
6	keep_removing	Lucerne, Genève	1112790453	6953348454	0.160037
7	keep_removing	Biel/Bienne, St. Gallen	1112789885	6733341140	0.165266
8	keep_removing	Zug, Fribourg	1112788310	6583518417	0.169026
9	keep_removing	Zug, St. Gallen	1112786306	6489314963	0.17148
10	keep_removing	Basel, Genève	1112785341	6241049828	0.178301
11	keep_removing	Basel, St. Gallen	1112784384	6060231517	0.183621
12	keep_removing	Fribourg, Winterthur	1112781582	5869499462	0.189587
13	keep_removing	Baden–Brugg, Lausanne	1112779722	5646297857	0.197081
14	keep_removing	Lucerne, St. Gallen	1112776463	5525176188	0.201401
15	keep_removing	Zug, Basel	1112772417	5416097129	0.205457
16	keep_removing	Zurich, Genève	1112769114	5115149416	0.217544
17	keep_removing	Zug, Bern	1112763746	5000503847	0.22253
18	keep_removing	Winterthur, Lausanne	1112759901	4741437720	0.234688
19	keep_removing	Baden–Brugg, St. Gallen	1112756332	4633785166	0.24014
20	keep_removing	Lucerne, Lausanne	1112749491	4444164097	0.250384
21	keep_removing	Bern, St. Gallen	1112738082	4235693570	0.262705
22	keep_removing	Winterthur, Biel/Bienne	1112725648	4075943432	0.272998
23	keep_removing	Fribourg, Basel	1112712791	3956285378	0.281252
24	keep_removing	Biel/Bienne, Genève	1112699142	3778350650	0.294493
25	keep_removing	Biel/Bienne, Lucerne	1112659368	3668988264	0.303261
26	keep_removing	Fribourg, Lucerne	1112638497	3544997217	0.313862
27	keep_removing	Fribourg, Zurich	1112562689	3379582597	0.329201
28	keep_removing	Winterthur, Lucerne	1112488050	3300346955	0.337082

29	keep_removing	Fribourg, Baden–Brugg	1112378940	3145606734	0.353629
30	keep_removing	Basel, Lausanne	1112327903	2963337054	0.375363
31	keep_removing	Zug, Winterthur	1112173023	2910391508	0.382139
32	keep_removing	Fribourg, Biel/Bienne	1111968310	2860378727	0.388749
33	keep_removing	Winterthur, Basel	1111906877	2745662446	0.404969
34	keep_removing	Baden–Brugg, Biel/Bienne	1111765550	2626127943	0.423348
35	keep_removing	Zurich, Lausanne	1111670432	2392530243	0.464642
36	keep_removing	Bern, Genève	1111389484	2219538952	0.50073
37	keep_removing	Zurich, Biel/Bienne	1110808680	2082902277	0.533299
38	keep_removing	Winterthur, Bern	1110477076	1928825436	0.575727
39	keep_removing	Biel/Bienne, Basel	1110006886	1857654556	0.597531
40	keep_removing	Biel/Bienne, Lausanne	1109319342	1746375252	0.635212
41	keep_removing	Baden–Brugg, Lucerne	1108756252	1682586295	0.65896
42	keep_removing	Lucerne, Basel	1107436527	1578305798	0.701662
43	keep_removing	Winterthur, St. Gallen	1106444106	1511991356	0.731779
44	keep_removing	Fribourg, Genève	1106432872	1375674529	0.804284
45	keep_removing	Baden–Brugg, Winterthur	1105280314	1333535606	0.828834
46	keep_removing	Bern, Lucerne	1102714017	1243445433	0.886821
47	keep_removing	Baden–Brugg, Bern	1100245017	1125298849	0.977736
48	stop_removing_bca	Zug, Baden–Brugg	1099400561	1075515746	1.022208

Appendix 7-9 Adjacency matrix link swapping

	Zug	**Fribourg**	**Baden–Brugg**	**Winterthur**	**Zurich**	**Bern**	**Biel/Bienne**	**Lucerne**	**Basel**	**St. Gallen**	**Lausanne**	**Genève**
Zug	0	0	1	0	1	0	0	1	0	0	0	0
Fribourg	0	0	0	0	0	1	0	0	0	0	1	0
Baden–Brugg	1	0	0	0	1	0	0	0	1	0	0	0
Winterthur	0	0	0	0	1	0	0	0	0	0	0	0
Zurich	1	0	1	1	0	1	0	1	1	1	0	0
Bern	0	1	0	0	1	0	1	0	1	0	1	0
Biel/Bienne	0	0	0	0	0	1	0	0	0	0	0	0
Lucerne	1	0	0	0	1	0	0	0	0	0	0	0
Basel	0	0	1	0	1	1	0	0	0	0	0	0
St. Gallen	0	0	0	0	1	0	0	0	0	0	0	0
Lausanne	0	1	0	0	0	1	0	0	0	0	0	1
Genève	0	0	0	0	0	0	0	0	0	0	1	0

Appendix 7-10 Adjacency matrix link deletion

	Zug	**Fribourg**	**Baden–Brugg**	**Winterthur**	**Zurich**	**Bern**	**Biel/Bienne**	**Lucerne**	**Basel**	**St. Gallen**	**Lausanne**	**Genève**
Zug	0	0	1	0	1	0	0	1	0	0	0	0
Fribourg	0	0	0	0	0	1	0	0	0	0	1	0
Baden–Brugg	1	0	0	0	1	0	0	0	1	0	0	0
Winterthur	0	0	0	0	1	0	0	0	0	0	0	0
Zurich	1	0	1	1	0	1	0	1	1	1	0	0
Bern	0	1	0	0	1	0	1	0	1	0	1	0
Biel/Bienne	0	0	0	0	0	1	0	0	0	0	0	0
Lucerne	1	0	0	0	1	0	0	0	0	0	0	0
Basel	0	0	1	0	1	1	0	0	0	0	0	0
St. Gallen	0	0	0	0	1	0	0	0	0	0	0	0
Lausanne	0	1	0	0	0	1	0	0	0	0	0	1
Genève	0	0	0	0	0	0	0	0	0	0	1	0