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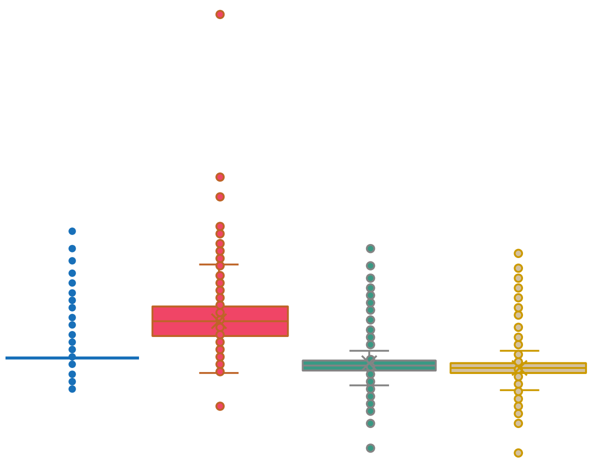
MASTER'S THESIS

Modeling Transit Commuters' Short-Term En-Route Replanning Behavior in Response to Unexpected Service Disruption



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Topic: Modeling Transit Commuters' Short-Term En-Route Replanning Behavior in Response to Unexpected Service Disruption

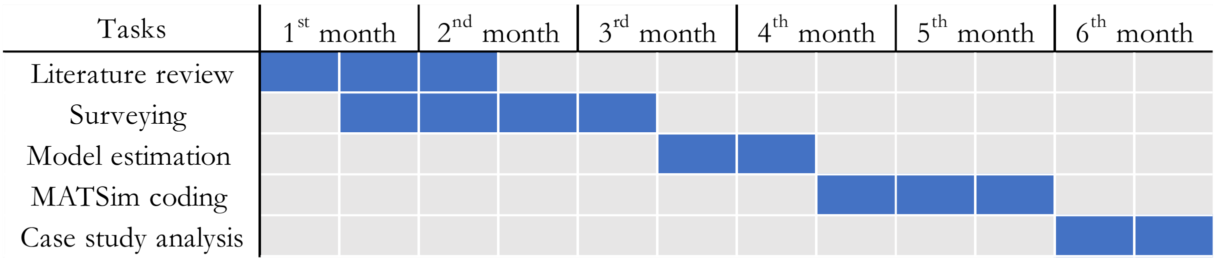
Public transport (PT) systems serve as the backbone of the mobility in many cities because they carry people to their desired destinations more efficiently and sustainably than motorized private vehicles. Many cities consider the implementation of PT a solution to reduce dependency on cars. In order to encourage the use of PT, such systems are operated according to established routes and timetables, so that travelers can schedule their trips conveniently prior to departure. Moreover, the PT services should be delivered punctually; otherwise, the users cannot stick to their scheduled plan. Nevertheless, PT systems sometimes encounter particular events that interrupt service regularity. Such disruptions cause different levels of negative impacts on the PT systems and unavoidable behavioral changes of the PT users.

The impacts caused by the PT disruptions could be long-term or short-term. The long-term impact is the reduction on PT ridership, which is a habitual behavioral change on mode choice (Lin et al., 2016). The short-term effect, however, is more complicated and dynamic according to Van Exel et al. (2001). They stated that PT riders' short-term trip replanning strategies contain mode shifts, route changes, destination changes and trip cancellations. Considering the complexity and diversity of the short-term trip diversions, Nielsen (2011) also argued that different magnitude of the disruptions may lead to different reactions. Although the disruptions have a wide variety, PT users perceive those events in terms of time and make replanning strategies based on predicted delay. Therefore, the research question "to what extent does the duration of service disruption correlate with the commuters' short-term en-route replanning behavior?" is proposed.

The research in this thesis is to investigate public transit commuters' short-term en-route behavioral change in responses to unplanned system breakdown. The expected goal is to find out the correlation between time duration and short-term en-route replanning behavior. In order to answer the research question, scenarios with different disruption durations will be designed for testing respondents' replanning decisions. This research focuses especially on PT commuters because commuting trips are generally mandatory and therefore more sensitive to system disruptions. The other focus is on the en-route disruption events, which make commuters even less flexible in reactions. A better understanding on the en-route replanning behavior of commuters could help transit agency to design accident-responsive multimodal PT systems with substitute replacement services. A practical contribution of this research is to mitigate the unwanted long-term reduction on PT ridership and enhance the reliability of PT.

To accomplish this thesis, literature regarding contributors to short-term behavioral changes will be reviewed. Then, a stated preference survey based on the literature review will be designed to collect passengers' en-route replanning decisions under different disruption durations. Trip characteristics, social economic status of commuters, familiarity of PT system and ITS system will also be included. Later on, a discrete choice analysis method, especially conventional statistical methods, will be applied in model estimation. Finally, the estimated en-route replanning model will be integrated into the MATSim platform for real world case study. The timeline of this thesis is proposed and shown in Table 1.

Table 1 Timeline of the thesis



The student will present intermediate results to the 1st mentor (Nico Kühnel) in the fifth, tenth, 15th and 20th week.

The student must hold a 20-minute presentation with a subsequent discussion at the most two months after the submission of the thesis. The presentation will be considered in the final grade in cases where the thesis itself cannot be clearly evaluated.

List of References:

Lin, T., Shalaby, A., & Miller, E. (2016). Transit user behaviour in response to subway service disruption. Annual Conference - Canadian Society for Civil Engineering, 4, 3151–3161.

Nielsen, L. K. (2011). Rolling stock rescheduling in passenger railways: Applications in short-term planning and in disruption management (Doctoral dissertation). Erasmus University Rotterdam, Rotterdam.

Van Exel, N. J. A., & Rietveld, P. (2001). Public transport strikes and traveller behaviour. Transport Policy, 8(4), 237–246.

1st Mentor: Nico Kühnel

2nd Mentor: Prof. Dr.-Ing. Rolf Moeckel

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Abstract

Due to the car traffic problems in urban regions, many cities continue developing public transportation (PT) as their mobility backbone. PT system is expected to provide reliable service to promote sustainable travel behavior. However, such system sometimes encounters particular events that interrupt the service regularity. Such disruption might cause delay, rerouting of services, and service cancellation. This thesis aimed to model trip replanning behavior of PT commuters and the research question is „To what extent does the duration of service disruption correlate with the rapid rail commuters' short-term en-route replanning behavior?" This research focused on the behavior of PT commuters, including home-based work and home-based education trips, in the Munich Metropolitan Region.

To tackle the research question, a status quo investigation, including interview with main PT operator and disruption data collection, was conducted. Important findings from the investigation was then considered in the stated preference (SP) survey design. The SP survey was the data collection method of commuters' preference in trip replanning. The survey contains 3 scenarios, namely 10-, 20-, and 60-minutes disruption, and 7 replanning options, including "Stay & wait", "Use another PT line", "Use my own car", "Use carsharing", "Take taxi", "Cancel the trip", and "Other". After the data collection, a multinomial logit model was estimated, which was also applied in a case study for testing its applicability.

In total 476 complete and valid responses were collected. The model estimation results indicated that the effect of additional travel cost becomes less negative as disruption time increases. As to the effect of delay time, it depends on replanning options. For "Stay & wait", the effect of delay time becomes worse as disruption time increases. For the other options, delay time's coefficient rises as disruption time increases. Travel time, occupation, car availability, driving license possession, and carsharing membership also influence commuters' trip replanning behavior. Last but not least, the case study also proves plausibility of the model.

The findings of this research are consistent with hypothesis: commuters react to service disruption differently in terms of perceived additional travel cost and delay time. The case study was also aligned with the findings. However, the share of choosing "Use my own car" in the case study might be underestimated. The MATSim PT assignment result should be validated to verify the application of the model on case study.

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List of Abbreviations

DB	Deutsche Bahn
ICT	Information and communication technology
ITS	Intelligent transportation system
MMR	Munich Metropolitan Region
MVG	Münchner Verkehrsgesellschaft
MVV	Münchner Verkehrs- und Tarifverbund
PT	Public Transportation
RP	Revealed preference
SC #	Scenario #
SC	Stated choice
SP	Stated preference

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Chapter 1

Introduction

"Liber Fahrgäste,
derzeit kommet es auf den genannten Linien wegen einer Betriebsstörung zu
Verspätungen und Ausfällen. Wir entschuldigen uns für die Verzögerung.
Ihre MVG
(Public announcement of Münchner Verkehrsgesellschaft on the 19th of Nov. In 2019)"

Have you ever experienced the incident described above when commuting to your office, school, or university? On a usual weekday, the crowded Munich subway system was interrupted by a malfunctioned vehicle and the next train service was delayed for 20 minutes. When the information of the disruption was announced in the station, I observed that passengers reacted differently. Some passengers simply waited for the next train, while the others used their smartphone to search for other alternatives to get to destinations. Their different behaviors in response to the service disruption inspired this thesis's work. In following parts of this chapter, motivation of this research, research question, research scope, expected contributions, and the organization of this thesis are presented.

1.1 Motivation

Many urban regions are suffering from car traffic problems, such as congestion, air pollution, noise, traffic accidents and so on (Greene & Wegener, 1997) . To partly overcome the problems, promoting the use of public transportation (PT) has been considered a feasible solution because it carries people to their destinations more sustainably and efficiently than private vehicles. Therefore, many cities continue developing PT as their mobility backbone, so that the car traffic and its related environmental externalities can be reduced (Litman, 2013).

To make PT an attractive commuting option is not an easy task. Compared with private cars, a major drawback of using PT is the time uncertainty (Mishalani et al., 2006). To reduce the time uncertainty, such system is usually operated according to timetables. Passenger could conveniently schedule their trips prior departure. Other than that, information and communication technology (ICT) has been widely implemented nowadays to provide passengers real-time information (CIVITAS, 2019). With such information, they can dynamically schedule their trips en-route. All the efforts are intended to make PT reliable to passengers.

Despite the many efforts, PT services are not reliable to passengers all the time. PT systems sometimes encounter particular events that interrupt the service regularity. Such disruption might cause delay, rerouting of services, and service cancellation. In the short run, right at the moment of service disruption, passengers either need to wait for the next PT service or re-plan their trips. Their replanning options could be using another routes or driving their own car, which is the worst case to the environment (Van Exel & Rietveld, 2009b). In the long run, such disruptions cause passengers' habitual change on mode choice according to Lin et al. (2016). PT passengers' reduced perception on PT's reliability results in the reduction in PT ridership and the shift to car traffic, which could worsen the environmental and living condition in urban regions (Greene & Wegener, 1997).

How should we deal with PT's service disruptions and avoid negative impacts? A very straightforward solution is to prevent any disruption; however, preventing disruption events completely is not possible because many of them are not predictable and avoidable in advance. In author's own opinion, understanding how passengers react to service disruption and providing effective alternative services to compensate the short run impact can be another solution. This idea brought up my motivation in studying **passengers' short-term en-route replanning behavior in response to PT service disruptions**. Understanding passengers' replanning behavior is the foundation for further development of effective alternatives.

1.2 Research question

Several interesting research questions were coming up during the scoping phase of this thesis: Would passengers react to any disruption no matter how long the duration is? Would passengers choose the second fast options even though they need to change to another mode? Would passengers be willing to pay more money in order to reach destination on time? All these questions are worthy of investigating, but the main research question of this thesis is fixed as: **To what extent does the duration of service disruption correlate with the rapid rail commuters' short-term en-route replanning behavior?**

Due to the variety of service disruptions, the duration of service disruption varies a lot. Some might take only few minutes; others might take several hours or even days. It is very interesting to know how passengers' reaction change according to delay time. The hypothesis made in this thesis is that **PT users react differently toward different disruption times**.

1.3 Research scope

PT passengers' short-term en-route replanning behavior is a broad topic, which can comprise different spatial scale, various systems, and a variety of passenger groups. To keep this research within the framework of a master's thesis, study area and focus group were defined in the research scope.

1. Study area

   The City of Munich is the capital of the Free State of Bavaria, Germany, and is seen as an economic, business, industry, and education hub of the State (Bayerische Staatsregierung, 2019). Besides the City of Munich itself, it also has very strong connection with its neighboring cities and counties. Since 2007, 31 cities and counties formed the Munich Metropolitan Region (MMR) for fostering regional cooperation and development (Munich Metropolitan Region, 2020). According to Bundesagentur für die Arbeit (2019), there are around 1 million employees commuting not only within Munich (665,810) but also between Munich and its neighboring cities or counties (393,827) every day.

   To meet the traveling need across cities and counties, PT systems in Germany are usually organized by "Public Transportation Companies Association (in German: Verkehrs- und Tarifverbund)", which integrates PT services operated by various operators into a single network, service, and fare system. The PT service in MMR is mainly organized by the Munich Public Transportation Companies Association (in German: Münchner Verkehrs- und Tarifverbund, MVV). The study area of this research focused on the MMR area covered by the MVV network. Partner cities and counties on the outer fringe of the MMR are also included only if they are in the MVV network.

2. Focus group

   In the study area, several PT systems are operating, including Regional Railway, S-Bahn, U-Bahn, Tram and Bus. Due to the heterogeneity of different PT systems, this research focuses primarily on the rapid rail systems, namely the Regional Railway, S-Bahn, and U-Bahn, which has more similar characteristics. Also, the rapid rail systems are the main systems connecting passengers not only in the city center but also between the City of Munich and its neighboring regions. Furthermore, the focus group of this research is passengers who commute on the rapid rail system to work, school, or university. Since different trip purposes might have different characteristics, this thesis firstly focused on home-based commuting trips.

1.4 Goal, objectives and contributions

The goal of this thesis is to capture rapid rail commuters' complex en-route replanning behavior. To achieve the goal, a solid experiment needs to be designed and implemented to obtain sufficient data for model estimation. Furthermore, the collected data need to be estimated for shedding the light on commuters' en-route replanning behavior. Last but not least, the model's applicability is diagnosed by implementing a case study in the center of Munich.

The contribution of this thesis has twofold: From the viewpoint of academia, the model estimated in this thesis can complement current mode choice, route choice, and trip generation models, which usually aim for trip planning prior departure. From the practical point of view, this thesis contributes in developing a behavioral model in predicting commuters' behavioral change. The developed model can be further applied either for an effective disruption management or for efficient and risk-responsive network development.

1.5 Organization of the thesis

The thesis is organized as shown in Figure 1. Chapter 1 has presented the background and the thesis's setup. Relevant literature was reviewed and summarized in chapter 2. In chapter 3, the status quo investigation on PT's service disruptions in the study area is presented. This chapter is to help readers gaining the background knowledge about the current situation in the study area. Chapter 4 contains the methods used in this research, which includes stated choice experiment design, discrete choice analysis and case study. Then, data collected for this thesis are described in Chapter 5. Chapter 6 and 7 present the model estimation result and case study. Last but not least, the findings of this research are discussed and compared with other studies in Chapter 8 and conclusion are drawn in the same chapter as well.

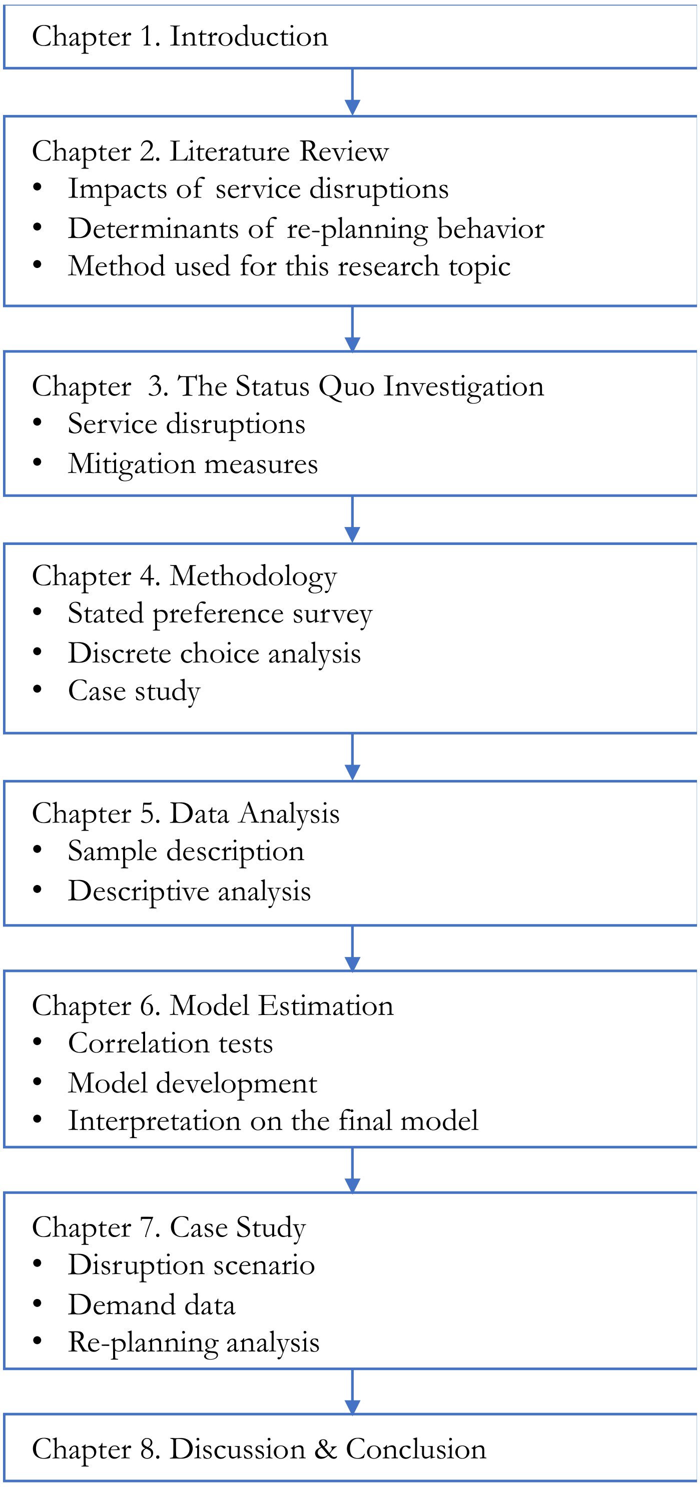

Figure 1 Organization of the thesis

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Chapter 2

Literature Review

Research related to PT service disruption have many focuses, such as network condition, transit ridership, mitigation strategy, information effect, service recovery duration, user waiting tolerance, and user response behavior (Rahimi et al., 2019). This research is especially focusing on the user response behavior or so-called replanning behavior, so the literature review surrounds this topic. This chapter include literature review regarding service disruption's impacts on PT users, influencing factors on their trip replanning behavior, and research methods that have been implemented on this research topic. The main purpose of this chapter is to identify research gap and search for suitable methods for this study.

2.1 Impacts of service disruption

When it comes to service disruption of PT, the impacts that we usually think of is delay or service cancellation. No matter it is delay or service cancellation, it influences PT users' behavior. A systematic understanding about that is to distinguish between long-term and short-term impacts on PT users' behavior (Nielsen, 2011). The difference between these two depends on when do PT users change their behavior and whether they change their behavior permanently or temporarily.

1. Short-term impact

   The short-term impact affects PT users right at the moment when they learn the information of service disruption and they need to make temporarily behavior change in response to the disruption, such as depart later, take another route, use another mode, and cancel the trip (Lin et al., 2016). Van Exel & Rietveld (2001) reviewed strikes happened in 13 different cities, PT users in these 13 different cities had ever canceled their trip, switched their trip to car, or switched to other PT alternatives. They even found out that the short-term impact affected captive riders the most because they have no alternative options and less flexibility in departure or arrival times. Apart from strikes, Pnevmatikou et al. (2015) studied the short-term impacts of a 5 months-long subway closure event in Athens and obtained similar findings as Van Exel & Rietveld. PT users, who have less income and no alternative mode available, less likely to have other option. They also added that not all affected PT users would shift back to their usual behavior even when the disruption was over.

2. Long-term impact

   If PT users change their behavior permanently, the impact is so-called long-term impact, which is a permanent habitual behavioral change on mode choice or route choice. According to the same literature from Van Exel & Rietveld (2001) strikes contribute to 0.3 to 2.5% reduction on PT's market share in some cities. A more recent study Nazem et al. (2018) also obtained similar findings. They carried out a before-after study on a station closure event in Montreal. In their research, bus smart card data before and after the 4-months long station closure were analyzed and the result shows that most of the PT uses use the system again when the service was restored. However, the ridership did not meet level before the station was closed, even after four months of re-opening. The long-term impact could be even more drastic which might permanently change PT users' destination choice, household location or car ownership (Lin et al., 2016).

From the above two paragraphs, we can observe that service disruption has accumulative effect on PT users' behavior change. When PT users involve in service disruption too often or involve in a massive one, unwanted behavioral change is unavoidable, such as car ownership or preference in motorized vehicles. That's why there are already existing studies about the short-term replanning behavior research. However, most of the literature regarding the short-term impact on PT users' behavior focus on planned events, such as strikes and system closures. These events are usually announced beforehand, so PT users might be more and well prepared for doing their short-term trip replanning. But what would unplanned events affect their behavior?

To the best of our knowledge, unplanned or unexpected disruption on PT users' behavioral change has not been discussed extensively yet. Most of the research regarding the unplanned service disruption are focusing on management strategies on operators' side (Itani et al., 2019; Pender et al., 2013, 2014a, 2014b). The unbalance research works of the unplanned disruption between operation side and on demand side can be seen as a research gap in this topic. That's why this thesis is to model PT users' short-term replanning behavior in response to unexpected service disruption.

2.2 Modeling replanning behavior

To fill the gap of unplanned disruptions' short-term impact on PT users' behavior, the main task is to identify influencing factors. There are two groups of variables found in related research: one is common mode choice variables and the other is effects of intelligent transportation system.

1. Common mode choice attributes

   Nguyen-Phuoc et al. (2018) conducted a qualitative research to find out the causal contributing factors of PT users' trip replanning behavior considering PT breakdowns. They interviewed 30 PT users in Melbourne and classified factors into three groups, which are:

   - Individual-specific attributes: income, car ownership, car availability, number of adults in household and so on
   - Context specific attributes include travel time, travel cost, travel distance and so on
   - Journey specific attributes contain accessibility to PT stations and trip purpose

   These variables are similar to the those in usual mode choice model. Additionally, they also highlighted that PT users do not make replanning decisions by one factor alone, but with a combination of factors. The interplay of attributes was continuously mentioned by the interviewees throughout the whole interview.

   Similar findings were obtained in several qualitative studies as well (Bagloee et al., 2014; Lin et al., 2018; Mahmassani et al., 2003; Nguyen-Phuoc et al., 2018b), even though the variables that they used in the research were the same. The variables that literature used in their research are summarize in Table 2, Table 3, and Table 4. The tables are grouped by the classification of Nguyen-Phuoc et al. (2018).

   An additional point worthy to be mentioned is the presentation of attributes. The presentation of attributes may also influence research participants' perception. According to Barron et al. (2013) most of the studies in the transit industry usually present the attributes to research participant in operators' language and less user-oriented. For example, the variable of disruption time is very operator-oriented because respondents need to recalculate to their own delay time or estimated arrival time.

2. Effects of intelligent transportation system

   In addition to the variables mentioned above, some literature also considers the effects of intelligent transportation system. In order to make information accessible for rational decision making, ITS is developed to collect real-time data on sites and distribute immediate information to travelers. The implementation of ITS has been proved to have positive influence on the replanning decisions of motorized private vehicles (Abdel-Aty et al., 1997). As to the ITS applications in PT, ITS has been widely implemented in many cities to improve the service quality of PT (Dziekan, 2019; Dziekan & Kottenhoff, 2007). Few studies focused specifically on the effects of at-stop displays and pointed out that such devices delivering en-route traveling information help reduce the perceived waiting time significantly compared to no information provided (Zhang, 2010; Lu et al., 2018). Built on these researches, Bai & Kattan (2014) investigated the effects of ITS application on PT users' en-route replanning behaviors. Their research findings are consistent with previous findings and they extended further that the experience with advanced passenger information system and the experience with public transit system have effects on riders' replanning behavior.

In the study area, the utilization of ITS is very high. Almost every subway station is equipped with at-stop display and public announcement broadcast is usually used if there is a disruption. This thesis would rather use ITS as background condition and investigating PT users' short-term en-route replanning behavior. However, the scenario setting needs to be carefully facilitate. The scenario should be as customized as possible to reflect the real situation for each respondent. In the research of Lin et al. (2018) and Mahmassani et al. (2003), they used a scenario simulator to generate en-route incidents and presented the scenario to the research participants. Their participants then chose their preference based on the scenario presented.

Table 2 Individual-specific attributes

Literature	Age	Gender	Education	Car ownership	Driving license	Number of adults in hh	Car availability	Income	Occupation
Mahmassani et al. (2003)	X	X	X					X	X
Van Exel & Rietveld (2009)				X	X		X		
Bagloee et al. (2014)	X	X	X						
Bai & Kattan (2014)	X	X	X		X				
Nguyen-Phuoc et al. (2018)				X	X	X	X	X	
Nguyen-Phuoc et al. (2018b)				X	X	X	X	X	
Lin et al. (2016)	X	X	X	X	X	X	X	X	X

Table 3 Context-specific attributes

Literature	Travel distance	Travel time	Travel cost	Trip destination	Weather	Main mode	Flexibility	Familiarity	Frequency	Worktime
Mahmassani et al. (2003)								X		
Van Exel & Rietveld (2009)		X	X	X					X	X
Bagloee et al. (2014)	X	X						X	X	X
Bai & Kattan (2014)						X		X	X	
Nguyen-Phuoc et al. (2018)	X	X	X	X	X		X			
Nguyen-Phuoc et al. (2018b)	X			X	X				X	
Lin et al., (2018)	X	X	X	X		X				X

Table 4 Journey specific attributes

Literature	Access/egress	Trip purpose	Transfer	Familiarity of surrounding	Ticket
Mahmassani et al. (2003)				X	
Van Exel & Rietveld (2009)	X	X			X
Bagloee et al. (2014)					
Bai & Kattan (2014)				X	
Nguyen-Phuoc et al. (2018)	X	X			
Nguyen-Phuoc et al. (2018b)	X	X			
Lin et al., (2018)	X	X			X

2.3 Research methods

Few kinds of research method have been applied in this research topic. The most modern one is data-driven research method, such as analysing bus smart card data (Nazem et al., 2018). However, most of the research were done by survey methods. There are two types of survey methods: one is revealed preference and the other is stated preference. Their differences are described below.

1. Revealed preference (RP) survey

   RP survey collects what has happened to the respondent and what they have done. In this topic, RP survey collects respondents' last experience encountering service disruption. There are some advantages in using this method are. The most important pros is that the answer is reliable because it is the real behaviour from the respondent (Louviere et al., 2000). However, an assumption is that, respondents need to remember everything, even details. RP is not capable in capture the effect of new product, situation or hypothetical scenario because they are not existing yet. Also, RP data may having the problem of high correlation, such as the travel time and travel cost (Hensher et al., 2015).

2. Stated preference survey

   SP obtains people's preference by providing given scenarios, so the answer is not real but a hypothetical one. Compared with RP, SP provides many flexibilities in SP is in exploring new alternatives or scenarios. The implementation of SP is also more economical efficient that RP in terms of time and cost (Hensher et al., 2015). Correlation problem in the data can also be avoided if a careful SP experiment design is done. However, the biggest problem of SP is the unreliable answer. Respondents' answer and real behaviour might not be consistent. There are also some solutions to reduce the bias of SP data. The most common one is to introduce "None of above" to avoid forcing respondents make choice. The other is to combine RP and SP for model estimation, and their result is widely acceptable (Ben-Akiva et al., 1994).

Since this research is going to find out the correlation between disruption duration and commuters' replanning option, SP survey might be a suitable method. Commuters might remember when they usually depart from home and arrive at destinations. They may not remember the delay time that they encountered in the last service disruption.

Chapter 3

The Status Quo Investigation

To acquire a thorough understanding about the current situation in the study area, a status quo investigation was carried out in the beginning phase of this thesis. The investigation summarized two aspects of information: One is PT's service disruption in the research area and the other is the mitigation measures, which have been implemented in the past.

Since no related data are available for public use or for research purpose, the investigation was done by interviewing PT operators and collecting data manually from operators' websites. For the Interview, main operators in the study area, namely German Railway (in German: Deutsche Bahn, DB) and Munich Transport Cooperation (in German: Müchner Verkehrsgesellschaft, MVG) were invited. An interview with MVG was held in September 2019. Although only one operator was interviewed, the outcome is still representative because MVG operates most of the systems within the study area. The interview minutes with MVG can be found in Appendix A. For the service disruption data, they were collected carefully from six o'clock to ten o'clock on the weekdays from the November 13th to December 18th, 2019 on DB's and MVG's website. Since the websites updated information dynamically, the author might miss some data records. Nevertheless, the data are fairly enough for analysis and the data can be found in Appendix B.

3.1 Service disruptions

There is no hard-written definition of service disruption in MVG, but a general deliberation is that any service delay or cancellation happened in timetables. According to MVG, service disruptions can be distinguished into two groups: One is minor disruption, which influences a relatively small number of passengers with 10 to 15 minutes delay. The other is major disruption, which affects a larger number of passengers with up to an hour delay or even days. However, there is no clear threshold number of affected passengers to distinguish these two, said the MVG. The following paragraphs shed more light on service disruptions' causes, frequency, seasonality, and impacts based on the interview and collected data.

1. Frequency

   According to MVG, 89% of its services are delivered on time without any interruption and there are one to two major disruptions happen every month. MVG's argument is aligned with our data. Table 5 shows that 50 disruptions happened during the morning peaks in the data collection period, which is averagely two to three disruptions during the morning peak hours per day. Few of the disruptions happened during the data collection period were major disruptions: S-Bahn had 6 large disruptions, U-Bahn, Tram, and Bus had 2 respectively. The interview and the data both revealed that major disruptions happen less common than minor disruptions. This fact was then considered in the scenario design of this research.

Table 5 Frequency of service disruption on weekdays

Systems	Service Disruptions	Major Disruptions	Minor Disruptions
S-Bahn	20	6	14
U-Bahn	20	2	18
Tram	2	2	0
Bus	8	2	6
Total	50	12	38

Note: the numbers represent the number of disruption events instead of the number of affected lines. The classification of major and minor was done by author and the major disruptions include delay time longer than 15 minutes, change of line services, and large service cancellation.

Source: Deutsche Bahn AG; Münchner Verkehrsgesellschaft.

2. Causes

   What causes service disruptions? MVG pointed out some common causes and they are presented in Table 6. There are ten common causes, from which 6 of them are unexpected events and the other 4 of them are expected events.

   For the unexpected events, technical problems, weather, massive failures of specific vehicle mode, and accident pose problems on vehicles and infrastructures. Diseases like flu result in labor force shortage. High traffic density during peak hours interference Tram's and Bus's operation. Emergency medical service in train stations or trains also influence train's operation. From the data, the unexpected disruptions account for half of the total disruptions. Among all the unexpected disruptions, technical problems happened the most often in the rapid rail systems: 10 events in S-Bahn, 2 events in U-Bahn.

For the expected events, operation reason is the most commonly happened one. Operators cancel or adjust services based on available workforce and infrastructures beforehand. During the data collection period, 5 operational events occurred in S-Bahn and 18 events in U-Bahn. However, strikes, special activity events, and construction are the other reasons, but they didn't happen during the collection period.

Whether the disruption duration time correlate with causes or not? This argument cannot be fully justified yet, said the MVG. Based on this finding, the experiment design only considers the disruption duration without any cause.

Table 6 Causes of service disruptions

Causes	Event Type	Frequency				
		S-Bahn	U-Bahn	Tram	Bus	Total
Technical problems	Unexpected	10	2	2	0	14
Weather	Unexpected	0	0	0	0	0
Massive failures of specific vehicle mode	Unexpected	0	0	0	0	0
Accidents	Unexpected	0	0	0	4	4
Diseases	Unexpected	0	0	0	0	0
Emergency medical service	Unexpected	3	0	0	0	3
High traffic density during peak hours	Unexpected	2	0	0	4	6
Special activity events	Expected	0	0	0	0	0
Strikes	Expected	0	0	0	0	0
Construction	Expected	0	0	0	0	0
Operation reason	Expected	5	18	0	0	23

Note: the numbers represent the number of disruption events instead of the number of affected lines.

Source: Deutsche Bahn AG; Münchner Verkehrsgesellschaft.

3. Seasonality

   There is seasonal trend in the service disruption according to MVG. The interviewee pointed out that there are more infrastructure problems in the wintertime. During summertime, there are less riders because of the school break and the fact that weather is usually nice for using other transportation modes, so they have less risk and stress on the service disruption.

   Since seasonality of service disruptions exists, this factor should be clear addressed in the scenario design of the experiment. Since the survey recruitment took place in winter, winter was chosen as the scenario to let respondents have more realistic feeling.

4. Impacts

   According to MVG, service disruptions pose impacts on both passengers and operators. For passengers, they face delay, service cancellation, crowdedness on the next services, irregular waiting time interval, and misconnection. For the operators, they face more issues on coordinating vehicles and drivers. Since this research focuses on passengers' behavior, the following paragraph are targeted to the temporal and spatial impacts on passengers.

   The impacts of service disruptions are very case sensitive, especially for the U-Bahn system. Disruptions usually happen on a single location point, but the interference might be a corridor long because turnouts and belt tracks for coordinating and rerouting trains are limited. Hence it is hard to identify a general pattern of the impacts. The other important aspect pointed out by the interviewee is the location of disruptions. If disruptions happen in the city center or hub stations, where there are more alternative connections, impacts are less severe because passengers can reroute easily. However, impacts might be larger in rural stations or stations without any alternative connections.

3.2 Mitigation measures

Before implementing any mitigation measures, the operators need to identify service disruptions, including estimating disruption duration and scheduling arrival time of next services. According to MVG, they receive information from station staffs, train staffs, CCTV in control center, and their 5 mobile teams cruising around in the city. Usually their colleagues estimate the disruption duration and arrival time of next service based on their experience. Although there is a scheduling software for using, but the software is not compatible in real-time rescheduling. After the disruption duration and the next service's arrival time are determined, information is sent to the displays and broadcasted in the stations, applications in cellphones, and websites simultaneously.

As mentioned above, there is no standard playbook for mitigation measures. The implementation of mitigation methods is based on operators' experiences. According to MVG, their first priority is to maintain regular service on uninterrupted sections. Providing alternatives depends not only on the location of disruption but also on the system's flexibility. As to the location of the service disruption, usually no special solution or alternative measure are provided in the city center because passengers can choose another line or walk to another station easily. As to the flexibility of system, Bus and Tram can be replaced and rerouted easily by stand-by vehicles. However, U-Bahn is way more difficult because of the constraints of turnouts, depots, and belt tracks.

Despite the constraints of implementing replacement service on U-Bahn system, replacement service has been provided on the U2 line between Harthof and Feldmoching by Bus and U1/2 line between Hauptbahnhof and Wettersteinplatz by Tram. Also, MVG has once cooperated with taxi to provide replacement service for a interrupted tram line between Westfriedhof and Moosach. Even though there are some show cases of replacement services, MVG claimed that there is less playroom form them to react in the unexpected disruptions.

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Chapter 4

Methodology

To tackle the research question, several methods were combined systematically to tackle the research question. As Figure 2 shows, a stated preference (SP) survey was designed and implemented as the data collection method to obtain PT commuters' preference in their replanning behavior and the factors influencing their decisions. With the data, discrete choice analysis was applied to estimate commuters' replanning decision model. This model can justify the correlation relationship between commuters' replanning decisions and influencing factors. Last but not least, the estimated behavior model was applied for a case study in the City of Munich. Each method was explained and described in detail in the following.

4.1 Stated Preference (SP) Survey
- Questionnaire design
- Stated choice experiment
- Experimental design
- Data collection

↓

4.2 Discrete Choice Analysis (DCA)
- Correlation test
- Utility functions
- Model form

↓

4.3 Case Study

Figure 2 Framework of methodology

4.1 Stated preference (SP) survey

The SP survey of this thesis aimed to obtain commuters' replanning preference under different disruption scenarios and potential influencing factors. For this purpose, the SP survey includes not only the questions regarding commuters' personal and trip attributes but also incorporated a stated choice experiment to test PT commuters' sensitivity toward delay time and travel cost. Since the survey of this thesis was relatively complex, the whole design process is explained in detail. In 4.1.1, the questionnaire design is presented to provide an overview of this survey. 4.1.2 describes how the stated choice experiment was developed. 4.1.3 explains the experimental design, which can ensure sufficient statistical power on the SC experiment. Last but not least, the recruitment plan is demonstrated in 4.1.4 because survey recruitment is also a vital step.

4.1.1 Questionnaire design

The questionnaire was designed on "LimeSurvey", an interactive web-based questionnaire platform. LimeSurvey offers several functionalities; for example, coding function to show questions based on respondents' answers and validation function to prevent wrong answer based on some given inputs from the respondents. These two important functions enable the author to design customized and respondent-friendly survey. Apart from the questionnaire tool, the survey was developed both in English and German, so that the majority of the commuters can have equal access to the survey.

Suggested by the literature, the questionnaire collected 4 aspects of information from the PT commuters, which might have influences on their replanning behavior. The first aspect of information is commuters' daily working or studying routine, such as current employment status, core working or studying hour, working or studying hour per day, and home office possibility. The second aspect of information comprises their commuting habits; for example, which ticket they use, which PT lines they take, which station they get on board and alight, when do they depart and arrive, journey time, and frequency of checking passenger information system. The third aspect of information is the stated choice experiment. Respondents were presented with several choice tasks, and they were asked to choose one option which they would do in the reality. More details are explained later. The last part of the survey is about their personal attributes, such as age, gender, continent of origin, car availability, and driver license. A summary list of all the variables collected in the questionnaire can be found in Appendix C.

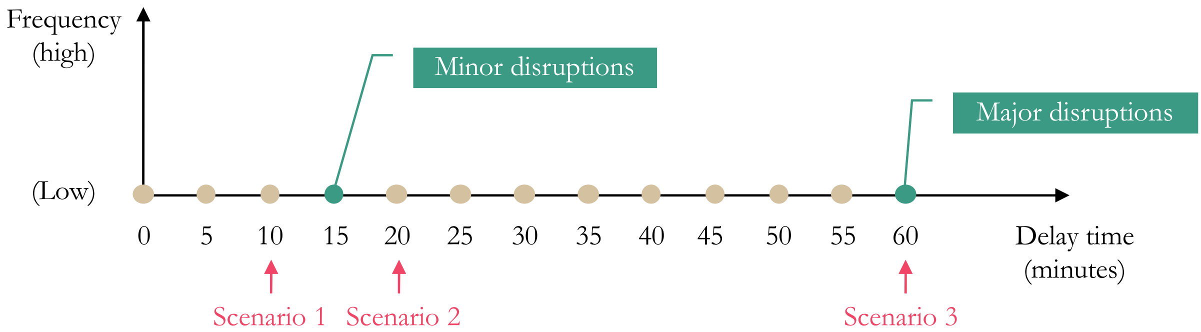
The survey temped to collected as much information as possible; however, a major challenge is the time consumption. Long survey decreases respondents' willingness to take part in the survey. Hence, the survey is targeted to be accomplished within 10 minutes, so that the willingness to answer the SP survey can be secured.

4.1.2 Stated choice (SC) experiment

After having the overview of the questionnaire design, this subsection explains the stated choice (SC) experiment in this survey. Designing an SC experiment involves several components: defining scenarios, identifying alternatives, selecting attributes, and determining attributes' levels. Each component is explained below.

4.1.2.1 Defining scenarios

The main objective in this survey is to capture commuters' replanning behavior under different duration of service disruptions. This research defined three scenarios as shown in Figure 3. According to the findings in Chapter 3, minor disruptions happen more frequently than major ones, so more scenarios were allocated to minor disruptions to capture the variance of the replanning behavior in response to minor disruptions. The first two scenarios were designed with **10- and 20-minutes delay** and these two scenarios can differentiate the 15-minutes delay argued by the interviewee. In addition, 10- and 20-minutes are the headway during peak hours in the U-Bahn or S-Bahn systems in the city center and outskirt respectively. The last scenario has **60-minutes delay** to represent major disruptions.



Note: the triangle area representing the frequency might not be real, and it is only for illustration purpose.

Figure 3 Scenario settings

During the interview, it is argued that causes of disruptions are not necessarily correlated with durations of disruptions, so the scenarios were only provided with delay time. No information about the causes of disruption event is provided. However, MVG interviewee stated that weather condition influences passengers' replanning behavior, so the scenarios were further specified with a constant weather condition. The weather condition here was specified as **a usual winter day without severe raining nor snowing**, which fitted quite well to the real weather condition when the survey was carried out.

4.1.2.2 Generating alternatives

Alternatives are the choices that respondents can make in the experiment, so the set of alternatives should contain all possibilities that respondents could have in the reality. Also, a set of universal and exclusive alternatives should be generated to achieve the rule of global utility maximization. However, it is impossible to include all possible alternatives and the number of alternatives should be remained within a reasonable level.

The alternatives of the replanning behavior focus on commuters' short-term trip replanning possibilities. The short-term en-route trip replanning involves no replanning, changing route, changing mode, and changing destination or activity as shown in Figure 4. The most common one is not doing any replanning, namely **"Stay & wait"**. If passengers need to re-plan their trips, they could simply change routes without changing the mode, namely **"Use another public transportation mode"**. If using another PT line cannot help them to recommence their trips, they could consider using another mode of transportation, such as driving or biking. Also, there are shared mobility available in the study area. All the available modes should be taken into consideration, but this research takes the modes associate with car traffic into account only because we want to catch the mode shift impact from PT to car. Hence, the mode change includes **"Use my own car"**, **"Use car sharing"**, and **"Take taxi"**. Additionally, commuters could decide not to go to the office, school, or university, so the option **"Cancel the trip"** is included. Last but not least, **"Other"** option is designed for selection if no options meet respondents' preference.

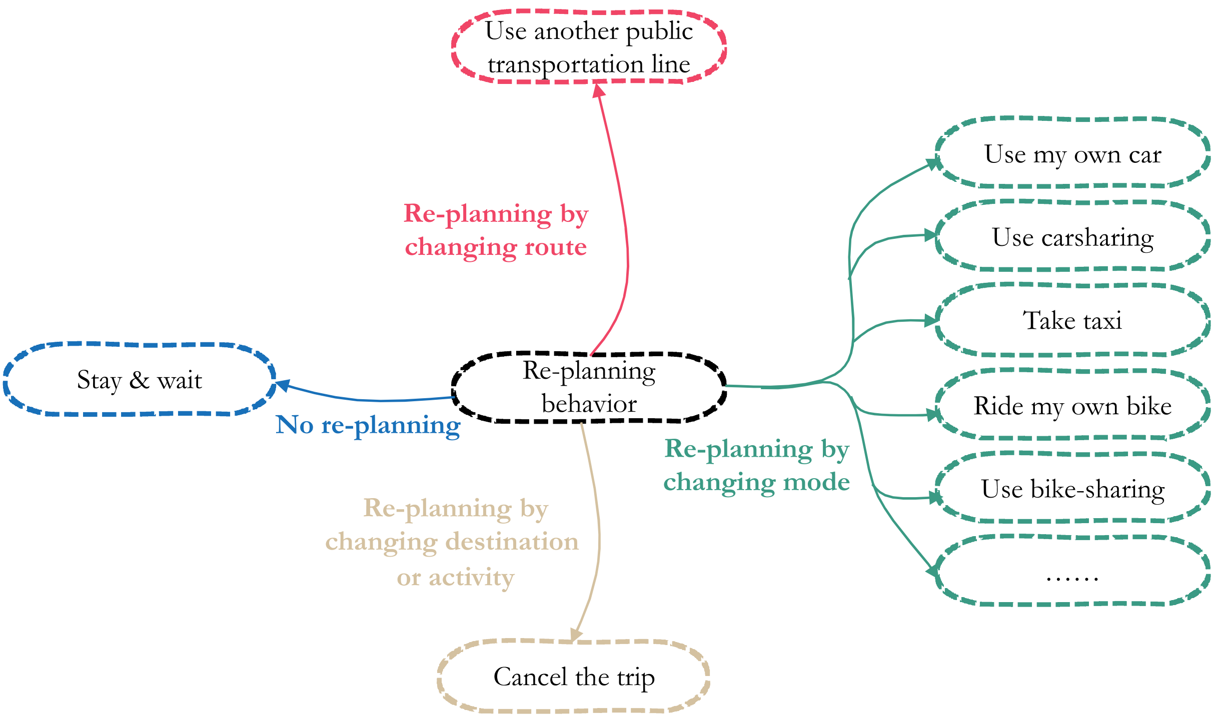


Figure 4 Replanning possibilities

4.1.2.3 Attributes

Attributes describe the characteristics of alternatives. This thesis selected 3 attributes to profile the alternatives. Travel time is a common attribute in typical mode and route choice model, but travel time is not directly perceivable to commuters in the case of en-route replanning. The delay time was used instead of travel time. The same as delay time, travel cost is also not correct in this case because commuters have paid already. The attribute of travel cost was named as additional cost to replace travel cost. The last attribute is the requirement for choosing this option. More details are described below.

1. Delay time

   When passengers do replanning, they usually compare the arrival time with original option. Barron et al. (2013) suggested to use the delay time for comparison; nevertheless, the delay time is still based on the calculation of travel time. The calculation of the travel time of each alternative is summarized in Appendix D. The calculation was based on the PT statistics, Taxi website, Carsharing operators' website, and the Molität in Deutschland 2017.

   Travel time usually comprises several components: access time, waiting time, in-vehicle time and egress time. Depending on alternatives, travel time of each alternative consist of different components. For example, "Stay & wait" has no access time because passengers are in the station already. "Use my own car" and "Use carsharing" have no waiting time and they can start their trips once they access to their vehicles. "Take taxi" has no access time but waiting time. For the option of "Cancel the trip" and "Other", the travel time is zero. The reference values of each mode are shown in Table 7.

   The access time in this case is understood as the travel time from current station to the location of next replanning option. For example, the access time of "Use another PT line" stands for the time from current PT station or platform to another platform or station where the services are still provided, which is 2 minutes in this case. "Use my own car" is the time from current PT station back to commuters' garage, which is 5 minutes in this study. The access time of "Use carsharing" is referenced at 5 minutes. Since taxi is dial service, so the access time is zero.

   The waiting time is the time that PT commuters wait for the service at locations. In the case of "Stay & wait", the waiting time is the disruption time in the scenarios, which are 10, 20, and 60 minutes. "Change to another PT line" takes the average headway of S-Bahn and U-Bahn systems as reference value, which is 8 minutes. "Use my own car" and "Use carsharing" have no waiting time. "Take taxi" has the waiting time of 5 minutes.

   The in-vehicle travel time for "Stay & wait" and "Change to another PT line" has same values, so do "Change to car" and "Change to carsharing". You may find this setting strange and this is the reason to add variance into attribute levels, which is explained later. As to “Take taxi”, it has shorter in-vehicle time than the other two car options because taxi passengers don’t need to look for parking spots.

After all the time components of each alternative are calculated, the travel time was summed up by all the components. Then, this thesis compared with the travel time of base alternative without additional disruption time to obtain the delay time. The delay time was calculated by deducting the travel time between the “Stay & wait” and the other alternatives.

Table 7 Reference values of delay time components

Alternatives	Access time (min.)	Waiting time (min.)	In-vehicle time (min.)	Egress time (min.)	Total travel time (min.)
Stay & wait	0	disruption time (10, 20, 60)	31	3	34+ disruption time
Use another PT line	2	8	31	3	44
Use my own car	5	0	29	3	37
Use carshar-ing	5	0	29	3	37
Take taxi	0	5	22	3	30
Cancel the trip	-	-	-	-	-
Other	-	-	-	-	-

Note: please refer to Appendix D for more explanations on the calculation of the values.

2. Additional travel cost

The travel cost in this thesis is ladled as additional travel cost because PT commuters has paid the transit ticket already. The calculation of the travel time of each alternative is summarized in Appendix E. Table 8 summarizes the reference value of additional cost for all alternatives.

For “Stay & wait”, there is no additional travel cost needed. As to the additional cost of “Using another PT line”, it depends on the tickets that passengers hold and how they re-route. This thesis first set the reference value to 0 because we assume that they can use the same ticket. However, this may not be the case, so variance was added in the attribute levels and is explained later. As to “Use my own car” and “Use carsharing”, the cost are 7.1 euro and 8.2 euro respectively. “Take taxi” costs the most, which is 34.8 euro. “Cancel the trip” and “Other” has no additional cost and left as empty in the table.

Table 8 Reference value of additional travel cost

Alternatives	Additional travel cost (euro)
Stay & wait	0.0
Use another PT line	0.0
Use my own car	7.1
Use carsharing	8.2
Take taxi	34.8
Cancel the trip	-
Other	-

Note: please refer to Appendix E for more explanations on the calculation of the values.

3. Requirements

   The last attribute to profile the alternatives is requirement. Requirement is the prerequisite that enables or allows passengers to choose this specific option. PT commuters cannot choose some specific options if some requirements are not met. For example, car, carsharing, and driving license should be available for commuters if they want to choose "Using my own car" and "Use carsharing". Otherwise, they cannot choose these options. The requirement is displayed in the survey to make respondents' selection more realistic. This attribute is more like a background and has no attribute levels.

4.1.2.4 Attribute levels

In the reality, the values of the delay time and additional cost may vary from person to person, so the purpose of defining attribute levels is to introduce possible variation range into the reference value calculated in the previous subchapter. This research determined 3 levels in the delay time and additional travel cost. The variation levels of each attributes are listed in Table 9.

1. Delay

   The variation of the time component is controlled by the total travel time, so the variance was introduced to travel time. Delay time was calculated again for each alternative. For "Use another PT line", the levels were pivoted around the reference value by -20%, 0%, and +20% (Vrtic et al., 2010). The other three car related options, their levels were pivoted around the reference value with -40%, 0%, and +40% according to Vrtic et al. (2010).

2. Additional travel cost

   The levels of "Use another PT line" were not pivoted by the reference value, because an assumption was made that some PT commuters might have a travel pass which is sufficient for re-routing. For them, the additional cost is always zero. However, some might need to buy additional "Anschlussticket" to travel beyond the purchased zone, which is 1.2 euros for 1 additional ring and 2.1 euros. This thesis assumed that passengers may exceed maximum 2 rings.

As to the levels of additional travel cost of car related options, the values were pivoted around the reference value by -30%, 0%, and 30% according to Vrtic et al. (2010).

Table 9 Variation levels

Alternatives	Delay time	Additional travel cost
Stay & wait	-	-
Use another PT line	(-20%, 0%, +20%)	(0, 1.2, 2.1)
Use my own car	(-40%, 0%, +40%)	(-30%, 0%, 30%)
Use carsharing	(-40%, 0%, +40%)	(-30%, 0%, 30%)
Take taxi	(-40%, 0%, +40%)	(-30%, 0%, 30%)
Cancel the trip	-	-
Other	-	-

The attributes and attribute levels of each alternative is summarized in Table 10. The delay time of “Stay & wait” is the scenarios, which are 10-, 20-, and 60-minutes delay, and the additional cost is always zero. For “Use another PT line”, the delay time are 2, 10, and 18 minutes, and the additional cost are 0, 1.2, and 2.1 euros. For “Use my own car”, the delay times are -11, 3, and 17 minutes, the additional cost are 4.9, 7.1, and 9.2 euros. For “Use carsharing”, the levels of delay time are the same as “Use my own car”, but the additional costs are 5.8, 8.2 and 10.7 euros. For “Take taxi”, the delay times are -15, -4, and 6 minutes, and the additional costs are 24.4, 34.8, and 45.3 euros.

Considering the delay time perception might not be so accurate and deterministic, the delay time of car related options were presented in an interval rather than value. For example, the delay time of “Use my own car” were presented as -15~-11, 0~5, and 16~20 rather than -11, 3, and 17.

Table 10 Alternative, attributes, and attribute levels

Alternatives	Delay time (min.)	Additional Cost (euro)	Requirements
Stay & wait (Wait)	(10, 20, 60)	0	-
Use another PT line (PT)	(2, 10, 18)	(0, 1.2, 2.1)	-
Use my own car (Car)	(-11, 3, 17)	(4.9, 7.1, 9.2)	Driving license Car availability
Use carsharing (Carsharing)	(-11, 3, 17)	(5.8, 8.2, 10.7)	Driving license Carsharing membership
Take taxi (Taxi)	(-15, -4, 6)	(24.4, 34.8, 45.3)	-
Cancel the trip (Cancel)	-	-	-
Other (Other)	-	-	-

4.1.3 Experimental design

After defining the attributes and attribute levels, there are 9 alternative-specific attributes (5 alternative-specific delay times and 4 alternative-specific additional travel costs) and each of them has 3 levels. If the SC experiment apply the full factorial design, the experiment has 3^9 (19683) treatment combinations, which is impossible for any respondent to finish. To make the experiment doable within 10 minutes and maintain the statistical power of the experiment at the same time, the size needs to be reduced scientifically. Orthogonal experimental design method was implemented to reduce the number of treatment combinations presented to respondents.

4.1.3.1 Experimental size reduction methods

Orthogonality is the golden rule for doing reduction on the experiment's size. Orthogonality means that the attributes, which are going to be estimated, have zero confounding or aliasing between each other. The idea can be imagining as that, there are 4 variables to be estimated and we need as much polynomials as possible and the polynomials shouldn't be identical. There are some experimental size reduction methods, which are explained and evaluated below.

1. Generating end-points design

   The simplest method to reduce the size of the experiment and maintain orthogonality is to generate an end-points design. End-points design means that only the two extreme values of each attributes, namely the minimum and maximum values, are kept in the experiment. In this research, the three-levels design will be reduced to two-levels design. The reference value of all attributes will be given up. However, end-points design is still not sufficient for this research. With end-points design, there are still 2^9 (512) treatment combinations. Although, the size decreases a lot but still beyond respondents' doable range.

2. Using fractional factorial design

   Another further approach to reduce the experimental size is to the fractional factorial design. This method is more difficult than what it literally explains, which is not merely take a fraction of the treatment combinations. According to Hensher et al. (2015) it is not recommended to take the fraction randomly. However, the first step is to determine which effects are going to be estimated. The effects can be understood as the parameters, which are going to be estimated in the model estimation. The effects in a model have several possibilities, such as main effects on each attributes or interaction effects between some attributes. According to sparsity-of-effects principle, main effects can contribute to most of the explaining power of the model. Hence, only a model with main effects were considered in this research. For each alternative, three parameters are needed for constant, delay time, and additional travel cost. However, people usually consider travel cost equally, so the parameter for travel cost is designed as alternative generic variable, while constant and delay time are alternative specific attributes. As to the alternative of "Cancel the trip" and "Other", no delay time and additional travel cost available, but constants are needed for these two. To sum up, 12 parameters need to be estimated for the main effects only model.

The number of parameters stands for the degree of freedom needed for the experiment. In this case, we need 12 degrees of freedoms, which stands for 12 treatment combinations at least. The size of the experiment has been reduced significantly. However, there are 3 scenarios in this research, so the respondents need to answer 36 choice sets in total, which is unfortunately still too much. Hence, further reduction is needed.

3. Determining the number of blocks

The final solution to reduce the experiment size is to do the blocking design. Blocking is to segment an experiment into several parts and assign several parts to different respondents. Once all segments are completed, a full sample is said to be successfully collected. The assumption of blocking design is that there is no difference across respondents. A major drawback of this method is that large number of respondents is needed. In this research, we divided the experiment into 3 blocks, so 3 respondents need to finish the 3 blocks to form a complete sample. However, each respondent was presented with 4*3 (treatment combinations * scenarios) choice sets in total.

4.1.3.2 Generation and evaluation of orthogonal experimental design

To generate and evaluate the experimental design of orthogonal design, the R package AlgDesign was applied in this research. The experimental design result is shown in Table 11. The table was shown in the effective coding: -1 means the lowest value, 0 means the reference value, and 1 means the highest value. The table only presents the treatment combinations of “Use another PT line”, “Use my own car”, “Use carsharing”, and “Take taxi” because the experiment was designed to replicate three times through the three scenarios. The last column is the blocking number. The blocking number is from 1 to 4 rather than 1 to 3 because one more block is added based on the feedbacks from pilot survey. Respondents argued that 12 choice sets are too many, so the blocking size was increased to 4 at the end. Each respondent received 3*3 (treatment combinations * scenarios) choice set in total.

Table 12 shows the confounding (or aliasing, correlation) effect across all the variables. If two attributes are confounded, the value would not be zero. From the table, we can find that all the values are zero, expect for the diagonal values, so we can conclude that the experimental design is a proper design with sufficient statistical power.

Table 11 Orthogonal experimental design of this thesis

Treatments ID	Delay time				Additional travel cost				Block Nr.
	PT	Car	Carsharing	Taxi	PT	Car	Carsharing	Taxi	
1	1	1	-1	-1	1	-1	-1	-1	1
2	-1	-1	-1	1	-1	-1	1	1	1
3	-1	1	-1	-1	1	-1	-1	1	1
4	-1	1	1	1	1	1	1	-1	2
5	1	1	1	1	1	1	1	1	2
6	1	-1	1	-1	-1	1	-1	-1	2
7	1	-1	-1	-1	-1	-1	-1	1	3
8	-1	-1	-1	1	-1	-1	1	-1	3
9	-1	1	1	-1	1	1	-1	1	3
10	1	-1	1	1	-1	1	1	1	4
11	-1	-1	1	-1	-1	1	-1	-1	4
12	1	1	-1	1	1	-1	1	-1	4

Note: the table is presented with the effective coding, except for the column of blocking number. -1 stands for the lowest value of the attribute, 0 is the reference value, and 1 is the highest level.

Table 12 Confounding between attributes

Attributes		Intercept	Delay time				Additional travel cost			
			PT	Car	Carsharing	Taxi	PT	Car	Carsharing	Taxi
Intercept		1	0	0	0	0	0	0	0	0
Delay	PT	0	1	0	0	0	0	0	0	0
	Car	0	0	1	0	0	0	0	0	0
	Carsharing	0	0	0	1	0	0	0	0	0
	Taxi	0	0	0	0	1	0	0	0	0
Additional cost	PT	0	0	0	0	0	1	0	0	0
	Car	0	0	0	0	0	0	1	0	0
	Carsharing	0	0	0	0	0	0	0	1	0
	Taxi	0	0	0	0	0	0	0	0	1

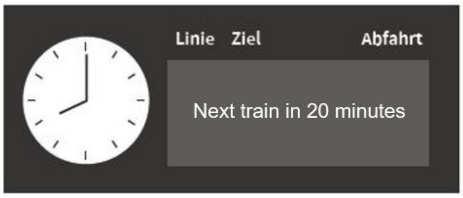
Note: the values is the confounding coefficient between two variables. 0 stands for no confounding and 1 means confounding.

4.1.3.3 Experimental setup

The last step of the experimental design is how the experiment is set up. The demonstration of the experiment was shown in Figure 5. The experiment's setup was customized by using the data provided by the respondents, such as trainset lines, departure station, arrival time, and the latest arrival time. The estimated arrival time of each option is also show with the original arrival time plus delay time or minus by earlier arrival time. Also, the system disruption time is shown in a graphic similar to the at-station display to make the situation more realistic.

You are waiting for the **U2** line at the **Theresienstraße** station and you plan to arrive at your destination at **08:00**. Also, you need to be there **before 09:00**.

Suddenly, the on-platform display shows:



Please consider the following re-planning options and their features, such as additional cost, estimated arrival time and requirement. Then, choose what you would do.

Re-planning decisions	Additional cost	Estimated arrival time	Requirement
Stay & wait	0 €	08:00 +20 min.	-
Use another public transport line	+1.8 €	08:00 +1 min.	-
Use my own car	+5.0 €	08:00 -15~-10 min.	Car & driving license
Use carsharing	+6.0 €	08:00 -15~-10 min.	Carsharing Abo & driving license
Take taxi	+32.0 €	08:00 -20~-15 min.	-
Cancel the trip	-	-	-
None of above	-	-	-

Figure 5 Experiment setup

A validation mechanism is also applied for detecting invalid selection of options. If respondents claim that they have no car or no driving license, they cannot choose "Use my own car". If they have no carsharing subscription, they cannot use carsharing. All these efforts are made to make the experiment respondent more reliable. Also, the sequence of the choice sets was randomized to reduce the experimental bias.

4.1.4 Data collection

After finishing the survey, SC experiment, and orthogonal experiment design, the stages of the data collection were carried out. The first phase is the pilot survey and the second phase are the formal survey.

4.1.4.1 Pilot survey

The pilot survey was aiming at identifying potential problems of the questionnaire. 25 pre-selected participants, half from the transportation discipline and the other half from other disciplines, were invited to take part in the pilot. After they finished the pilot, they were invited to a one-to-one feedback session to share difficulties or confusion during the survey, such as confusions in experimental setting or difficulty in understanding questions. Their time spent on the pilot was also recorded.

Three key problems were identified during the pilot survey. The first problem is the confusion of experiment's treatment combinations. They are confused with the 12 scenarios and assume that the 12 choice sets are the same. Therefore, different color was added to the table to make some visual difference. The second problem is some unclear question, which has been improved by consulting the language writing center at the university. Last one is the time consumption, overall 12 minutes is needed, so some relatively unimportant question was crossed out. However, half of them reported that 12 choice sets are too much. Therefore, one more block was introduced to reduce the choice sets. The final survey can be found in Appendix F.

4.1.4.2 Main survey

A flyer was prepared to help recruit PT commuters to participate in the survey. You can find the flyer in the Appendix G. The survey was conducted from 14 November 2019 to the 5 December 2019. Commuters were randomly invited during evening peak hours on the weekdays. They received one-minute pitch about this research and this survey. If they were inspired and motivated to take part, they received a flyer and completed the survey on their own.

The data collection result is shown in Table 13. In total, around 900 flyers were distributed at 53 U-Bahn stations, 8 S-Bahn stations, and few business areas. 622 responses were received, of which 99 are incomplete and 522 are complete. The response rate is around 58%. After doing the validation check on the responses, another 47 responses were dropped, so in total 476 responses were used in analysis and model estimation, which is 76.5% of the completion rate. Since the experiment incorporating blocking designs, so the number of samples in each block is also shown in the table. Every block received exactly 119 responses. The sample size is quite astonishing within the limited time frame.

Table 13 Summary of data collection result

Items	Number
Flyer distributed	900
Respondents entered the survey	622
Incomplete surveys	99
Complete and validated surveys	476
-in Block 1	-119
-in Block 2	-119
-in Block 3	-119
-in Block 4	-119
Completed but not validated surveys	47

4.2 Discrete choice analysis (DCA)

After the data were collected, discrete choice analysis was applied to model PT commuters' re-planning behavior. The modeling approach used in this thesis is conventional statistical model because correlations between dependent and independent variables need to be investigated to answer the research question

4.2.1 Correlation test of independent variables

Before estimating the behavior models, correlation test was conducted to identify the collinearity between independent variables. If two variables are correlated, only one of them would be selected for model estimation. Since the survey data have numerical and categorical type. Two different correlation tests were chosen for the analysis.

For the numerical variables, the Pearson correlation was implemented. Pearson correlation measures the linear dependence between two variables. The measurement is the correlation coefficient, which is a value between -1 and 1. If the correlation coefficient is 1, it means these two variables are positively correlated. If the values were -1, the two variables are negatively correlated. If the coefficient is close to 0, it means weak correlation between these two variables.

For the categorical variables, Chi test was applied to test the collinearity. The null hypothesis (H_0) of this test is that two variables are independent. The alternative hypothesis (H_a) means that the two variables are dependent. The measurement of the test is the p-value, which range from 0 to 1. If the p-value is less than 0.1, we could confidently reject the H_0 with 10% probability making an error. In another word, we need to accept that these two variables are not correlated if the p-value is higher than 0.1. The result of the correlation test is the input for variable selection in the model process.

4.2.2 Utility functions

The modeling suite used in this thesis is Biogeme because it allows more flexibility in defining the model specification (Bierlaire, 2018). Especially, two of the alternatives "Cancel the trip" and "Other" have no delay time attribute and no additional travel cost attribute, estimating these two options only with alternative specific constant is not possible in other modeling suites, like mlogit in R.

The conventional statistical model chosen in this research is logit model, and the model form is multinomial logit model (MNL). The MNL model relies heavily on the assumption of independence of irrelevant alternatives (IIA), which means all the alternatives should be independent from each other. This thesis assumes that all the alternatives are independent and IIA property holds.

The probability of choosing replanning option k is defined by equation 1:

$$P_k \qquad = \frac{e^{U_k}}{\sum_{i \in C} e^{U_i}} \tag{1}$$

where C is the choice set of the replanning alternatives, U_k is the utility of option k, and U_i are the utility of all alternatives. The model estimation process tries to find best feasible values on the utility parameters, which maximize the likelihood of the model to match the collected data.

The best feasible utility parameters are the parameters in the utility function. The utility of any given alternative i for any given individual q is shown in equation 2.

$$U_{iq} \qquad = V_{iq} + \varepsilon_{iq} \tag{2}$$

where U_{iq} is the total utility of alternative i for and individual q, V_{iq} is the perceivable utility, and ε_{iq} is the utility, which cannot be explained by the collected data. The perceivable utility is further explained in equation 3.

$$V_{iq} \qquad ASC_i + \beta_i X_i + \cdots \tag{3}$$

where ASC_i is the alternative specific constant, β_i is the alternative specific or generic utility parameter, and X_i is independent variable. The model estimation process is to find the best β_i to maximize the like hood of the model.

The utility functions need to be treated carefully in this thesis because some constraints were added on the model specification during the experimental design process. From the experimental design paragraph, the design of the model is main effects only model, so the delay and additional travel cost in the utility functions of each alternative should be the main effects and no interaction terms between these two variables are expected. The perceivable utility functions' base form of all alternatives is presented below from equation 4 to 10.

$$V_{wait} = \beta_{delay,wait} D_{wait} \tag{4}$$

$$V_{pt} = ASC_{pt} + \beta_{cost} C_{pt} + \beta_{delay,pt} D_{pt} \tag{5}$$

$$V_{car} = ASC_{car} + \beta_{cost} C_{car} + \beta_{delay,car} D_{car} \tag{6}$$

$$V_{carsharing} = ASC_{carsharing} + \beta_{cost} C_{carsharing} + \beta_{delay,carsharing} D_{carsharing} \tag{7}$$

$$V_{taxi} = ASC_{taxi} + \beta_{cost} C_{taxi} + \beta_{delay,taxi} D_{taxi} \tag{8}$$

$$V_{cancel} = ASC_{cancel} \tag{9}$$

$$V_{other} = ASC_{other} \tag{10}$$

All the alternatives have an alternative specific constant (ASC), except for "Stay & wait". The ASC of "Stay & wait" is set to zero as the reference value of other ASCs. The additional travel cost (C_i) is estimated as alternative generic parameters because the monetary cost is perceived equally on different mode or routes. Four of the alternatives contain this parameter, except for "Stay & wait", "Cancel the trip", and "Other". The second parameter in the base utility form is the delay time. Delay time is estimated as an alternative specific parameter because people may perceive time differently on different mode.

The later modeling process takes the utility functions above as base form. Other individual specific attribute is added one by one base on the result of correlation test.

4.3 Case study

After the model was estimated, the model was applied in a case study for testing the model's applicability. The replanning model developed by this thesis is integrated with existing modelling suite as Figure 6 shows.

1. Obtaining input trip data from existing modeling suites

   The replanning model was implemented in the Munich model developed in the Microscopic Transport Orchestrator (Moeckel et al., 2017). This research utilizes the generated travel demand from MITO as input data for the case study. Then, the input trip data was assigned onto road and PT network by using MATSim, which is a micro traffic assignment suite developed by (Horni et al., 2016).

2. Defining disruption scenarios

   A disruption case is defined, and transit service schedule is reviewed and modified based on the defined disruption case. This will be explained in the Chapter 7.

3. Identifying affected passengers

The assigned trip data was fed into an identifier to filter out the affected passengers. The identifier is a java class, which can read in the assigned trip and selects affected passengers based on predefined disruption scenarios. The identifier also labels whether passengers encounter service disruption on board or en-route.

4. En-route replanning

The last step is to let the affected passengers do trip replanning. The en-route replanning model is also coded in java. After the replanning, new plans of the passengers are generated automatically for further application.

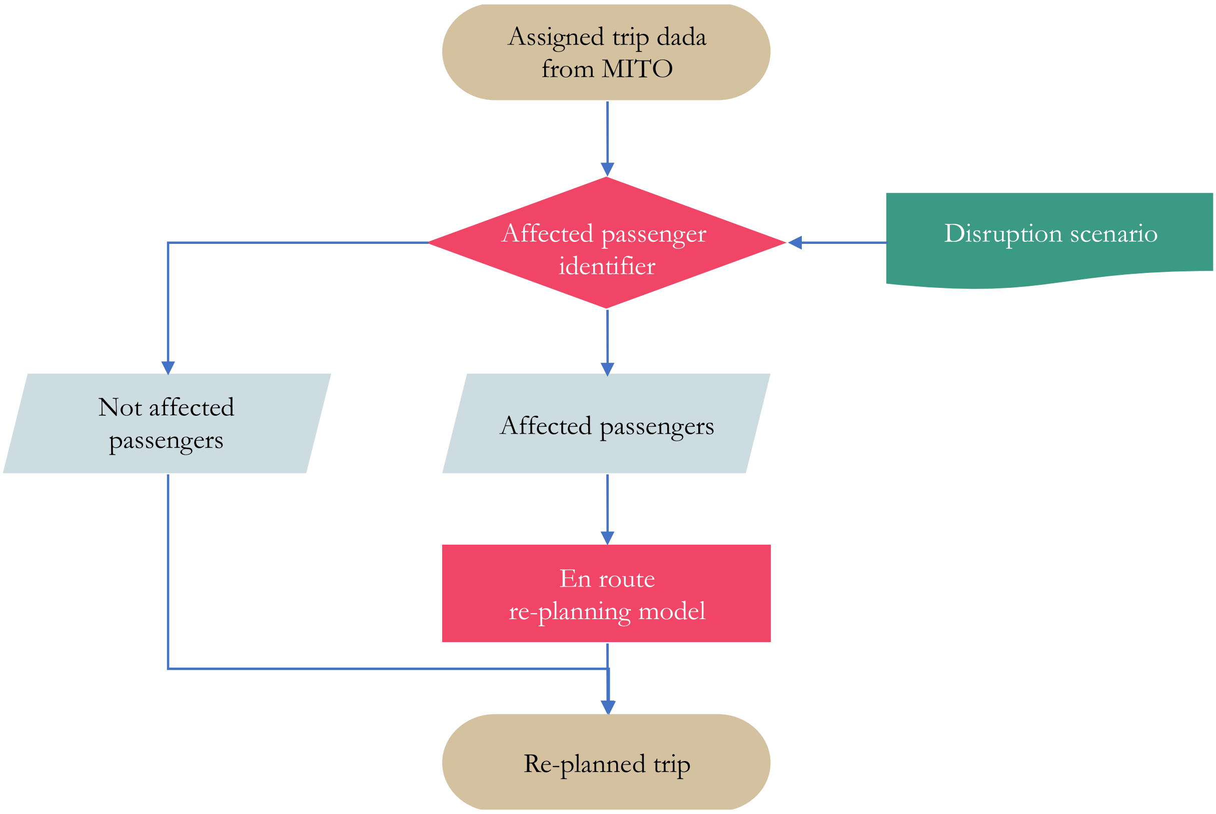


Figure 6 Model integration

Chapter 5

Survey Data Analysis

Data collected in this research covers four types of information: respondents' daily working/studying routine, their commuting trip characteristics, their preference in replanning options, and their personal attributes. This chapter describes the survey data which can be a useful step towards model development. In 5.1, the survey sample's personal attributes are described and compared with MiD 2017 to evaluate the representativeness of the sample. 5.2 sheds light on respondents' daily working/studying routine and commuting pattern. 5.3 summarizes the results of the stated choice experiment descriptively.

5.1 Sample description

A challenge with survey data is ensuring the sample is representative of the population. Normally, this can be achieved by comparing sociodemographic data from the survey (e.g. gender, age, and employment) with census data. However, the population of this research is PT commuters and census data does not differentiate by commuting mode. Therefore, MiD 2017 data were used as approximation. The comparison is summarized in Table 14 and each attribute is discussed below.

1. Gender

   In the sample, 51.3% of the respondents are female and 48.7% are male, while 46.4% of the population are female and 53.6% are male. Therefore, we observe that females were slightly overrepresented in this survey.

2. Age

   The 18-29 age group was significantly overrepresented in the survey, applying to 64.2% of respondents but only 32.2% of the MiD 2017 population. Ages 40 and above were underrepresented.

3. Employment

As the data show, the survey consists of half employees and half students, while the MiD2017 population is 74.1% employees and 25.9% students. This again shows the sample is not consistent with population.

Table 14 Comparison of research sample and population from MiD2017

Attributes	Labels	Survey	MiD2017
Gender	Male	48.7%	53.6%
	Female	51.3%	46.4%
Age	Under 18 years old	2.7%	9.8%
	18 – 29 years old	64.2%	32.2%
	30 – 39 years old	18.8%	20.9%
	40 – 49 years old	8.2%	15.5%
	50 – 59 years old	5.4%	17.0%
	60 – 69 years old	0.8%	4.2%
	70 – 79 years old	0.0%	0.5%
	Over 79 years old	0.0%	0.0%
Employment	Worker	50.5%	74.1%
	Student	49.5%	25.9%

To enable the survey to better represent the population, it is common to calculate expansion factors (or weights) for each record. These ensure the sociodemographic distribution of the sample and population are similar. Table 15 compares the distribution of sample and population, and the weights were calculated based on the table, and age groups over 50 were combined for weighting.

Table 15 Distribution of sample and population

Gender	Age	Sample		Population	
		Worker	Student	Worker	Student
Male	Under 18 years old	-	0.8%	-	5.3%
	18 – 29 years old	7.6%	21.5%	7.5%	9.0%
	30 – 39 years old	8.0%	1.7%	12.0%	0.2%
	40 – 49 years old	5.7%	-	8.5%	-
	Over 49 years old	2.9%	-	11.1%	-
Female	Under 18 years old	-	1.7%	-	4.1%
	18 – 29 years old	13.5%	21.3%	8.8%	7.2%
	30 – 39 years old	7.4%	2.3%	8.5%	0.1%
	40 – 49 years old	2.7%	0.2%	7.2%	0.1%
	Over 49 years old	2.7%	-	10.4%	-

5.2 Descriptive analysis

According to literature, commuters' daily working/studying routine and their commuting behavior might influence their replanning behavior, so a descriptive analysis was conducted on the weighted sample to understand the structure and characteristics of respondents.

5.2.1 Daily working/studying routine

Commuters' daily working/studying routines indicate the importance of their activity. This importance might be associated with their flexibility for replanning. Three questions were asked on this topic, and their statistics are presented here. Students and commuters are presented separately to provide a comparison between these two groups.

1. Daily working/studying hour

   Daily working/studying hour can represent how important respondents' daily activities are. Longer work/study hours might indicate that a commuter would make a greater effort to replan their commuting trip to reach to their destination. As Figure 7 shows, 73.5% of all the respondents have a full day working or studying routine. The majority of worker commuters (86.8%) have 8 or more than 8 working hours per day, while student commuters are 36.9%. About 15.7% of the student commuters have half day and less than half day studying activity, while only 3.2% of the workers are part-time employed.

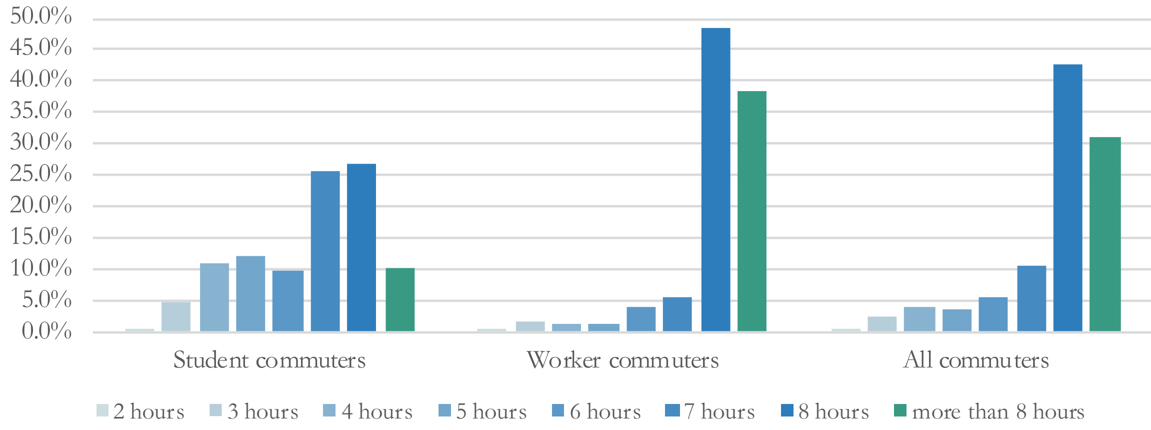


Figure 7 Commuters' daily working/studying hour distribution

2. Core working/studying hour

   If a commuter has a core working/studying hour, it means there is a time in which they must be at their destination. The response to this question indicates the urgency for commuters to reach destination on time. The results of this question are interesting and beyond expectation. Figure 8 shows that only 37.1% of the worker commuters have a core working hour, while 66.5% of the student commuters stated that they need to be in the school or university at a certain time. This goes against the assumption that students have more flexibility in replanning their trip than workers.

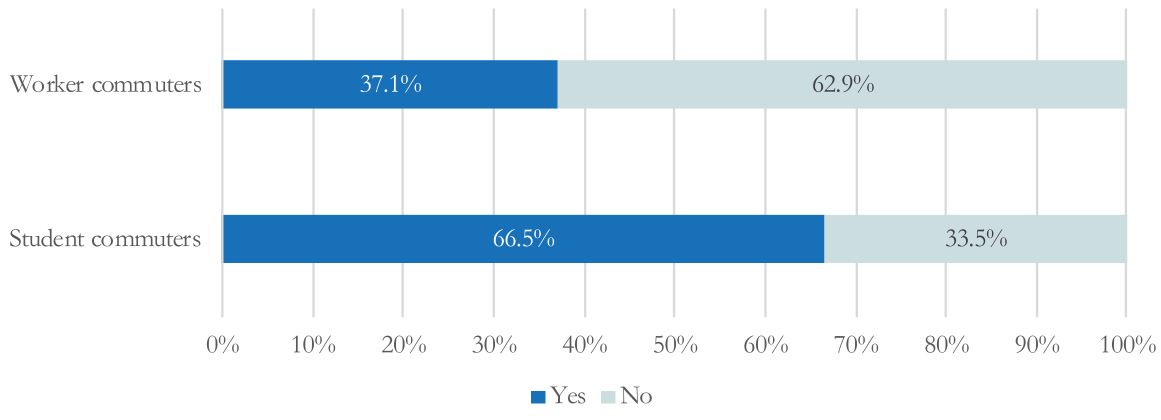


Figure 8 Commuters' core working/studying hour condition

3. Home office possibility

Home office allows employees to work from home. Home office may influence worker commuters' replanning behavior. Figure 9 shows that 60.6% of working commuters stated that home office is possible. However, some respondents said they only work from home on specific days or need to apply for allowance in advance. The extent that home office possibility affects worker commuters' replanning decisions is questionable.

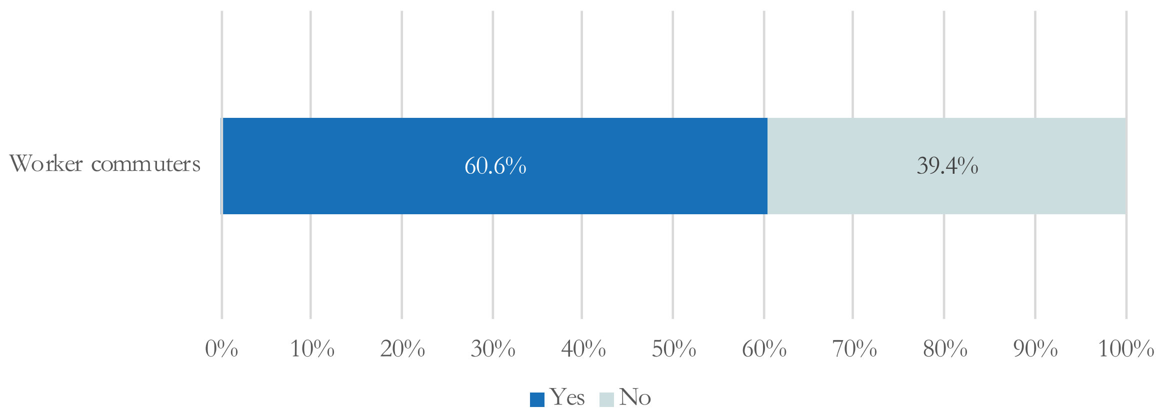


Figure 9 Commuters' home office possibility

5.2.2 Commuting trip characteristics

Commuters' flexibility in replanning decision also depends on the trip characteristics. By understanding commuters' trip characteristics, we could know how they travel and how they might travel in case of service disruptions.

1. Departure and arrival time

   Commuters' departure and arrival time might affect replanning behavior because there might be more alternative PT possibilities during peak hours than during off-pack hours. As Figure 10 shows, the departure time of student and worker commuters have a similar pattern, but worker commuters' departure is denser between 7 and 9 o'clock than student commuters. By 10 o'clock, which is around the end of the morning peak, 98.9% of the worker commuters and 96.5% of the student commuters have departed.

   Regarding arrival times, worker and student commuters also have similar pattern. Some differences are: 10.3% of the worker commuters arrive at their workplace before 6 o'clock, while no student commuters arrive at school or university before that time.

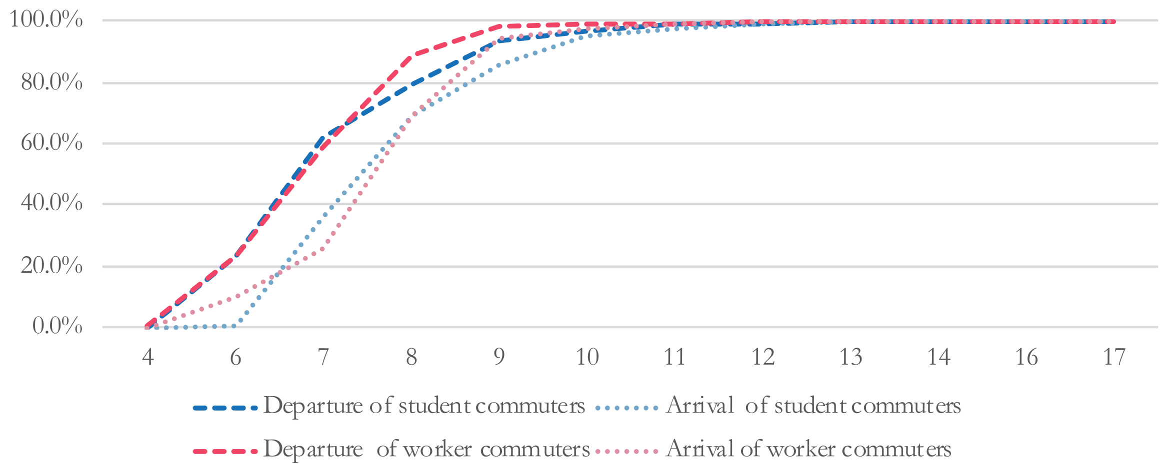


Figure 10 Commuters' accumulated departure and arrival time distribution

2. Travel time

   Commuters' travel time might also affect their perception of delay time and therefore replanning behavior because commuters with long travel times might perceive a 10-minutes delay differently than commuters with short travel times. Figure 11 shows the accumulated distribution of commuters' travel time. In general, student commuters have shorter travel time than worker commuters. The average travel time of student commuters is 37 minutes and 41 minutes for worker commuters. However, the data also shows that worker commuters commute no more than 95 minutes but there are some students who commute more that 1.5 hours.

Figure 11 Commuters' accumulated travel time distribution

3. Access mode

Access mode can potentially affect commuters' replanning behavior. Commuters that usually cycle to a rail or underground station might be more likely to cycle to their destination if there is a disruption. Figure 12 shows the access mode of commuters to the first station of their journey. Not surprisingly, most commuters walk to the 1st station (84.1% of student commuters and 72.9% of worker commuters). The 2nd most common access mode is bus, which is used by 35.3% of student commuters and 27.0% of worker commuters. The 3rd most common access mode is bike. It is worth pointing out that more worker commuters (21.5%) cycle to the 1st station than student commuters (15.8%). Access mode by car has a similar pattern to bike but the share is relatively small (5.6%). This suggests that most commuters would not have a car available at the station and would need to return home if they decide to drive.

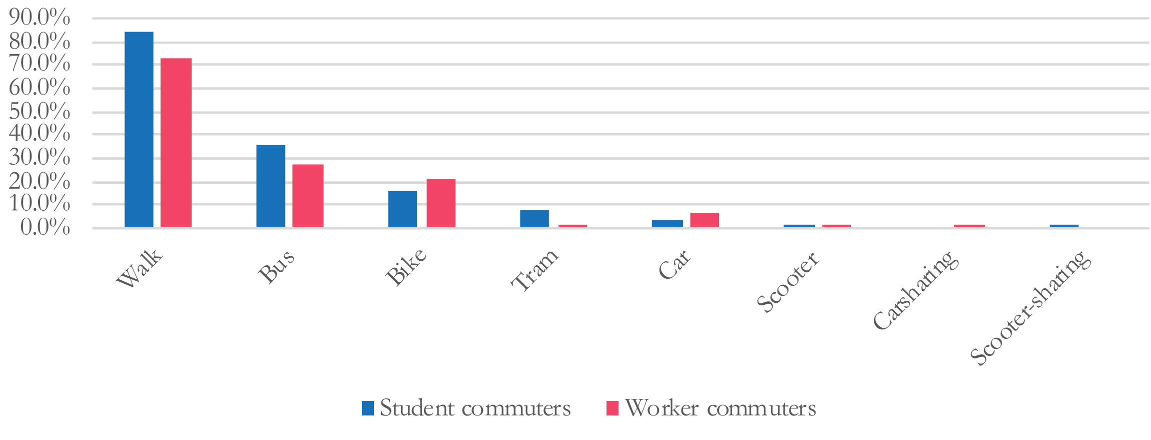


Figure 12 Commuters' access mode distribution

4. Access time

Access time could affect commuters' willingness to return home to use a privately-owned transport mode. As Figure 13 shows, around 31.8% of the student commuters and 40.6% of worker commuters have an access time of only five minutes. 78.9% of all commuters have an access time of 10 minutes or less.

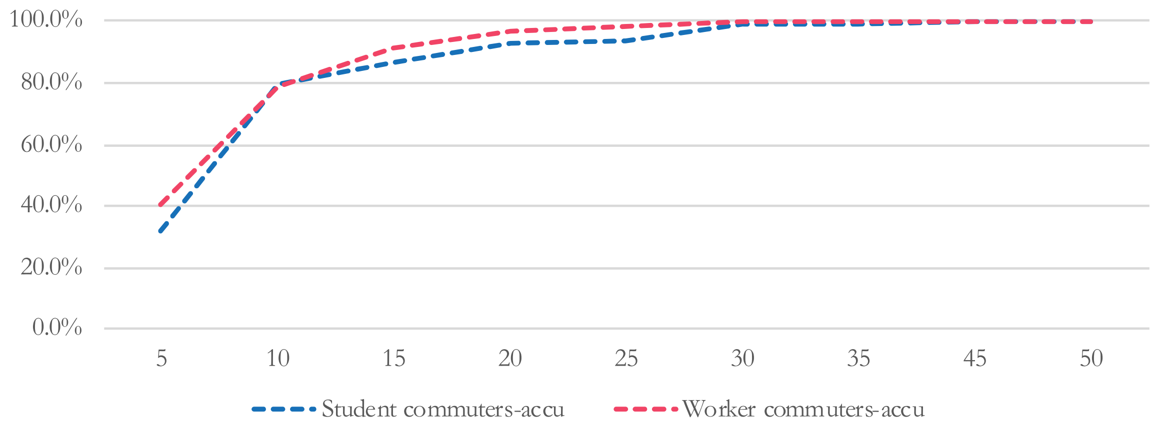


Figure 13 Commuters' accumulated access time distribution

5. Buffer time

The buffer time is the gap between commuters' actual arrival time and the latest allowable arrival time. This only applies to commuters with core working/studying hours. Longer buffer times probably indicate that a commuter would be less stressed during a PT disruption. As Figure 14 shows, around 18% of the commuters with a core working/studying hour leave no buffer in their commuting trip. Additionally, worker commuters tend to have longer buffer times than student commuters. 52.5% of student commuters have a buffer of less than 10 minutes as opposed to only 35.7% of worker commuters.

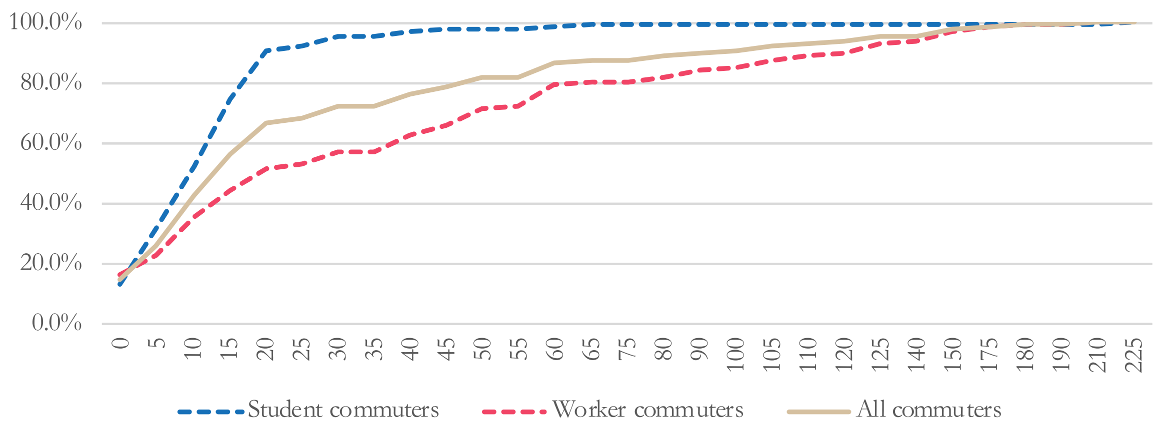


Figure 14 Commuters' accumulated buffer time distribution

6. Ticket

The type of PT ticket indicates how frequently commuters use PT. It also reveals whether they would need to pay more for further travel. People with travel passes are entitled to unlimited travel within their valid zones, so they could shift to other PT systems without additional costs. Therefore, the ticket type may affect replanning behavior. From Figure 15, more than 95% of both worker and student commuters have a travel pass.

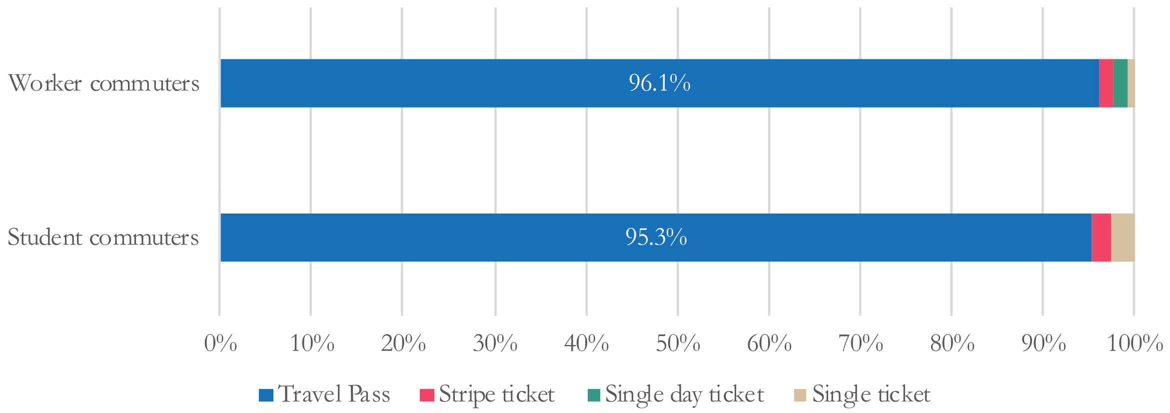


Figure 15 Commuters' ticket composition

7. Frequency of information acquisition

This statistic shows how often commuters acquire information about the operating status of PT systems. Figure 16 shows that 26.2% of worker commuters and 10.4% of student commuters never check the operation status via website or smartphone app prior to departure. Only 5.1% of the worker commuters and 10.5% student commuters always check the information before they leave their house. This suggests that most commuters would begin their replanning decision making process after arriving at the station.

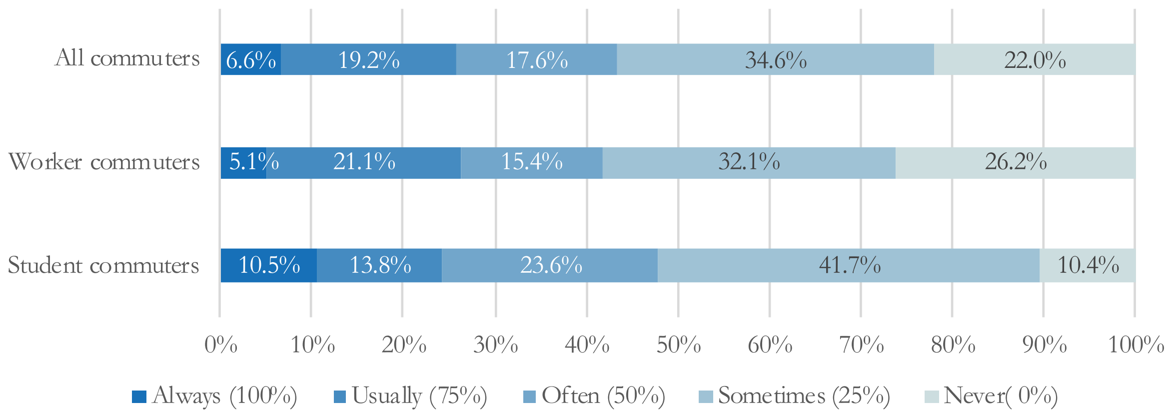


Figure 16 Commuters' frequency of information acquisition

5.2.3 Personal attributes

Decision models assume that individuals make rational decisions based on the characteristics of their options. However, this is not always true. Some other effects, such as commuters' personal attributes, might also influence replanning behavior. Here, we will look at the commuters' living years in the study area, mode availability, shared mobility membership, possession of driving license, and income.

1. Living years in study area

   Commuters' living years in the study area may correlate with their familiarity with the PT system and other transport alternatives. As Figure 17 shows, 66.4% of student commuters and 86.7% of worker commuters have lived in the research area for more than 2 years. However, 14.0% of student commuters have lived in the study area less than 3 months. Universities in the study area take in new students every 6 months, so it is not surprising to see a certain number of fresh commuters in the study area.

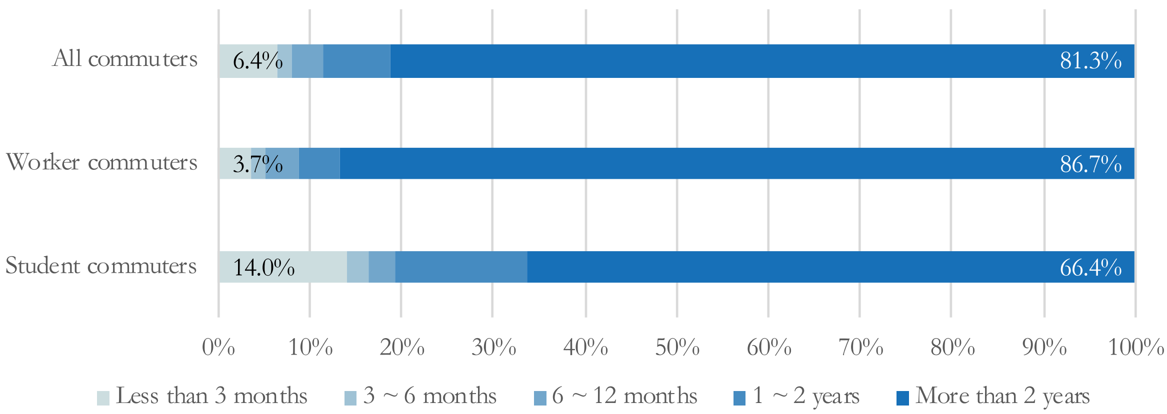


Figure 17 Commuters' living years in study area

2. Available transportation mode in household

   The availability of alternative transportation modes indicates the possibility for changing to other modes during a PT disruption. As Figure 18 shows, most commuters have access to a bike (71.5% of student commuters and 84.1% of worker commuters). Regarding car availability, more worker commuters (55.0%) have access to a car than student commuters (22.1%). Availability of scooters, motorcycles, and mopeds is relatively minor. Crucially, 25.0% of student commuters and 9.9% of worker commuters have no other transportation mode available. These are so-called captive riders whose options are limited to "Stay & wait", "Change to another PT", "Cancel the trip", and "Walking" when a disruption happens.

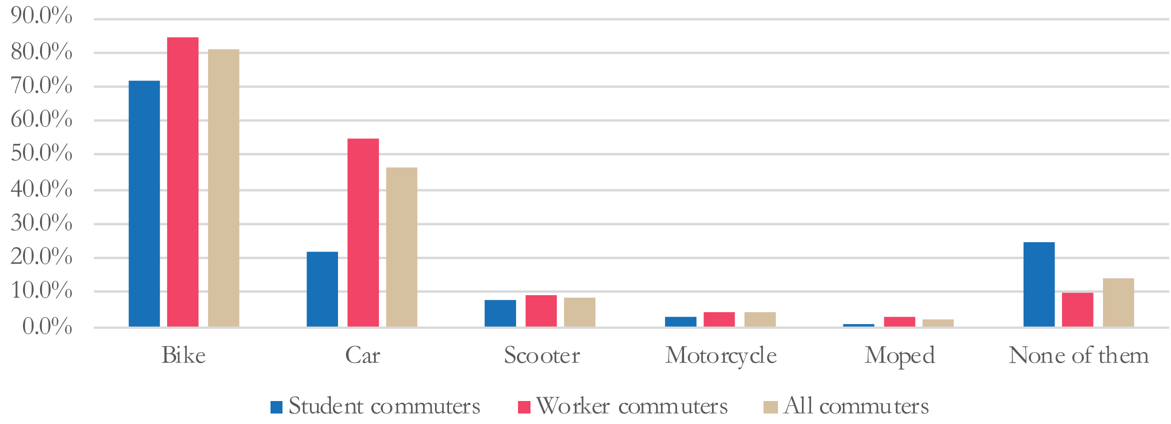


Figure 18 Commuters' available mode in household

3. Shared mobility subscription

Apart from privately-owned transportation modes, a shared mobility subscription is another way of accessing a car, bike, motorcycle, and/or scooter. At present, there are several shared mobility service providers in the study area such as DriveNow, MVG Bike, and Lime. From Figure 19, we can observe that shared mobility is still not common to commuters because 72.2% of the commuters have no shared mobility subscription. Regarding carsharing, 21% of worker commuters have a carsharing subscription while only 5% of the student commuters have one. E-scooter-sharing is generally less popular than car sharing, but more popular than bike sharing.

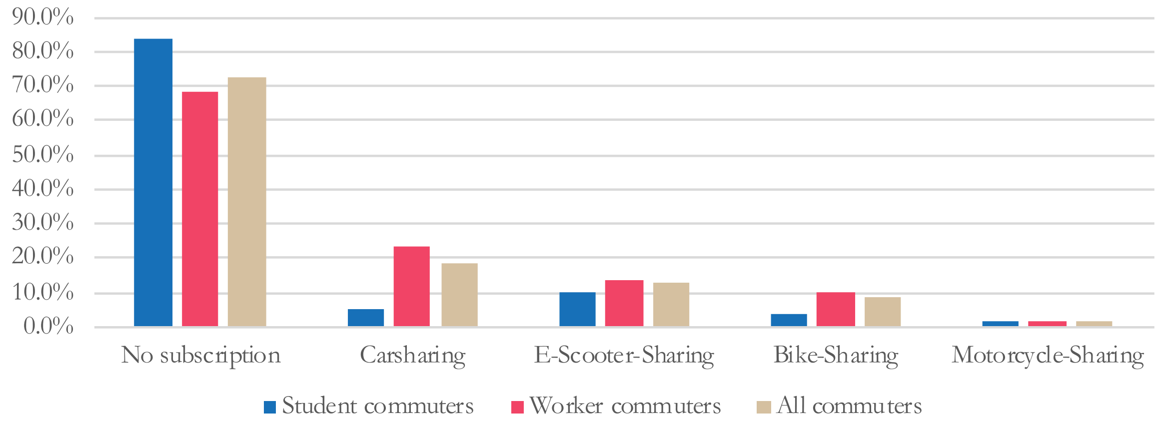


Figure 19 Commuters' shared mobility membership

4. Driving license

Having a driving license is likely an important prerequisite for shifting to car in response to a PT disruption. Figure 20 shows that 42% of student commuters and 81% of worker commuters have car-driving license. However, 52% of student commuters and 12% of worker commuters have no form of driving license.

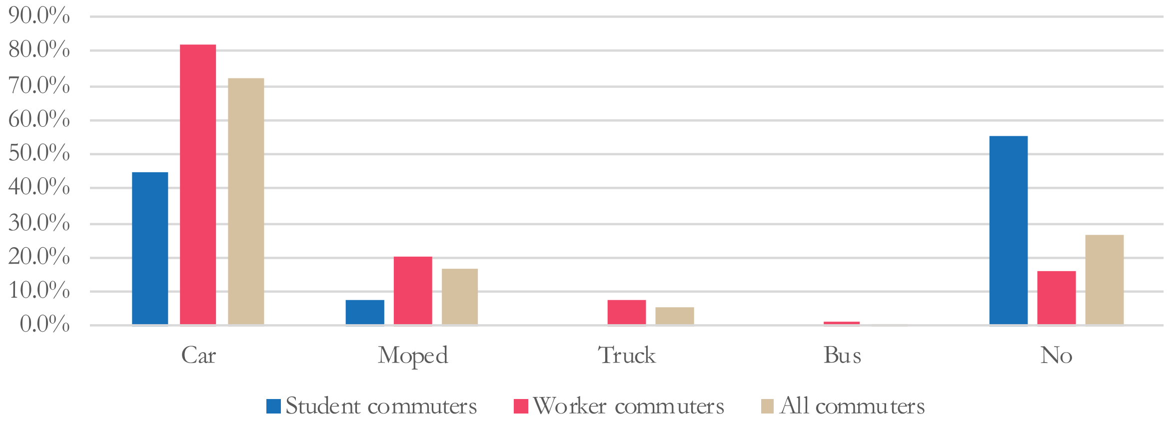


Figure 20 Commuters' possession of driving license

5. Income

Income also affects how much additional cost commuters can afford for replanning. Figure 21 shows the obvious difference between student commuters' and worker commuters' income. For the student commuters, most have monthly income less than 450 euros. On the other hand, workers have a bell-shape distribution. The average income is between 2000 to 3000 euro.

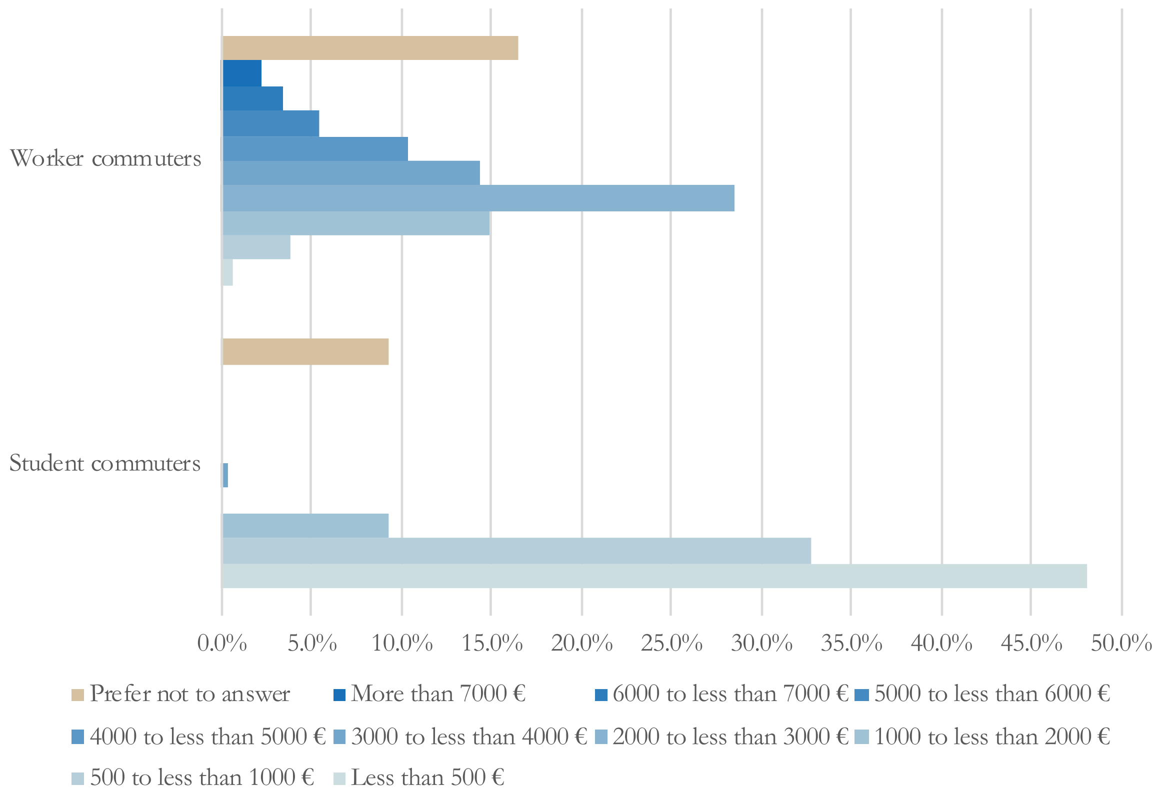


Figure 21 Commuters' income distribution

5.3 Insights on the replanning behavior

The last part of this chapter sheds light on the preference data collected in the survey. As Figure 22 shows, the frequency of the no replanning option decreases as disruption time increases, while all the other replanning options increase. Similar patterns are observed for student commuters and worker commuters. However, there is still some nuance, which is discussed below.

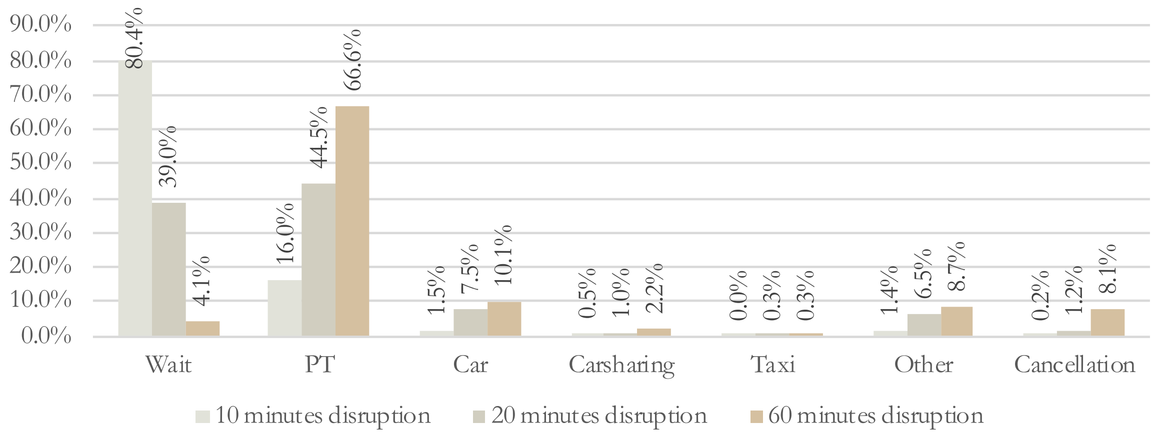


Figure 22 Commuters' preference on replanning behavior

1. Stay & wait

   As Figure 23 shows, student and worker commuters' preference of "Stay & wait" have the same changing trend across disruption times. There is no clear difference between worker commuters and student commuters in the 10 minutes disruption scenario; however, worker commuters are slightly less likely to "Stay & wait" when the disruption goes higher than 20 minutes.

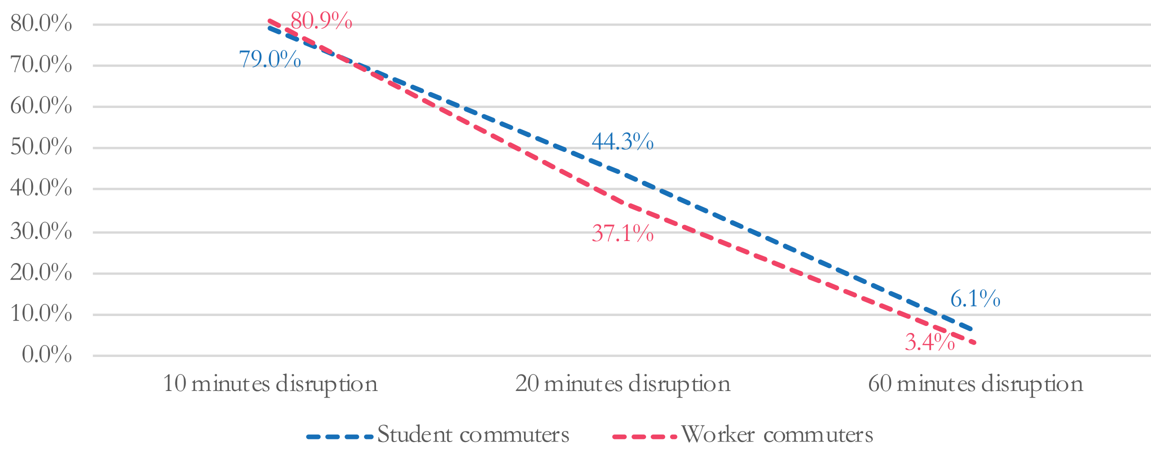


Figure 23 Preference of" Stay & wait" across different disruption times

2. Change to another PT line

As Figure 24 shows, the trend of worker and student commuters' preference on "Change to another PT line" have similar pattern. The difference between these two groups is not obvious, but worker commuters' tendency to choose this option is slightly lower.

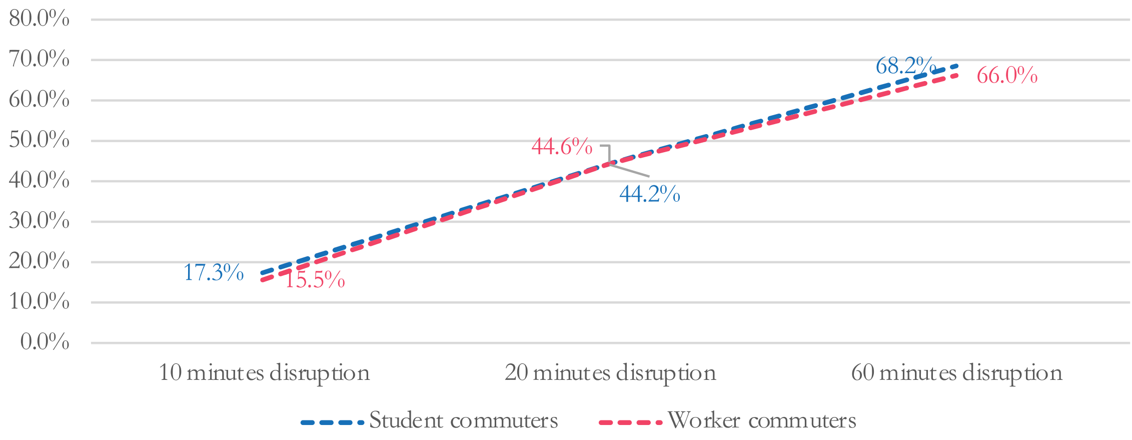


Figure 24 Preference of "Change to another PT line" across different disruption times

3. Use my own car

The frequencies of choosing "Using my own car" is smaller than the previous two options, especially for the student commuters. The preference of student commuters increases from 0.3% in the 10 minutes scenario to 1.7% in the 20 minutes scenario and remains at 1.7% in the 60 minutes scenario. However, the worker commuters have higher preferences on the car mode, which are 2.0%, 9.6%, and 13.2% respectively.

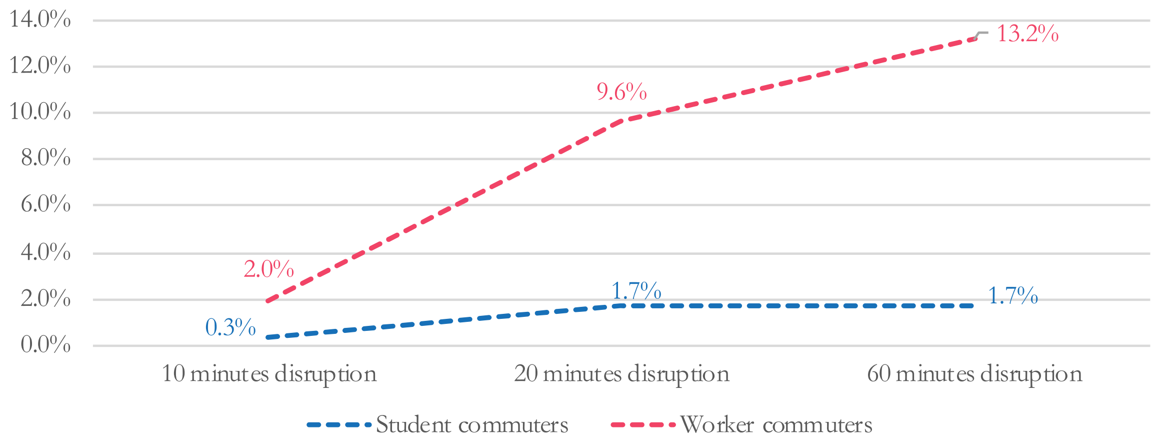


Figure 25 Preference of "Use my own car" across different disruption times

4. Use carsharing

Regarding carsharing, Figure 26 reveals an even lower probability than "Use my own car". There is an increasing trend for both student and worker commuters, but the share is very low. For the 60-minute disruption scenario, only 2.7% of worker commuters and 0.7% of student commuters chose this option.

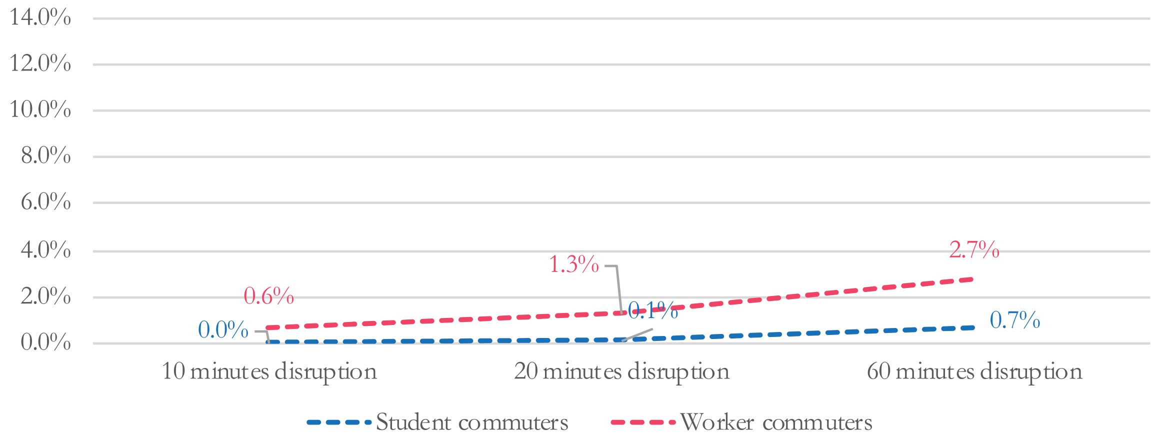


Figure 26 Preference of "Use carsharing" across different disruption times

5. Take taxi

Taxi is least preferable of all the options. For worker commuters, the probability of choosing taxi increase from 0.1% to 0.2% and 0.3%. However, the probability of student commuters increases from 0.0% to 0.4% and then decreases to 0.2%. After investigating the data, we observed that the student respondents who chose to take a taxi in the 20 minutes scenario chose to cancel their trip in the 60 minutes scenario.

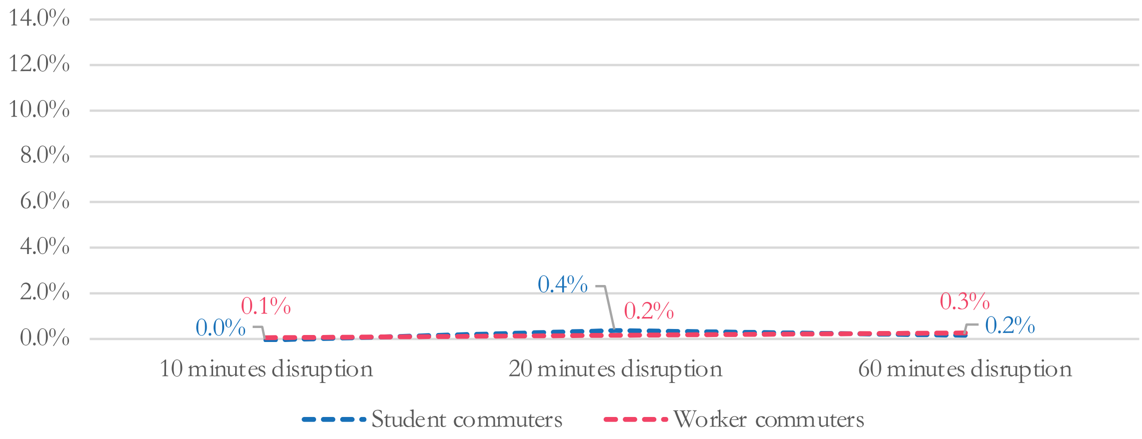


Figure 27 Preference of "Take taxi" across different disruption times

6. Other

According to the survey, the "Other" option here stands for bike and walk. As Figure 28 shows, student commuters tend to choose this option more than worker commuters across all the different scenarios.

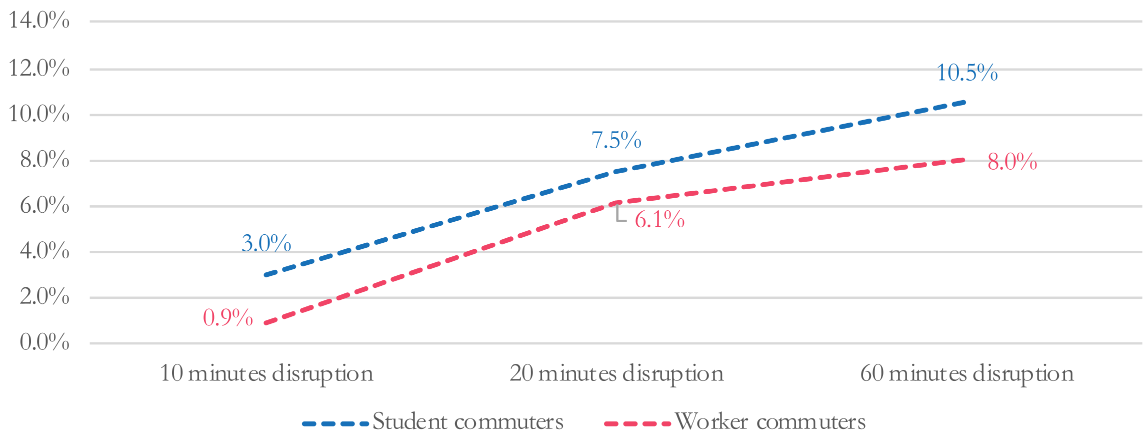


Figure 28 Preference of "Other" across different disruption times

7. Cancel the trip

The trend for "Cancel the trip" is shown in Figure 29. In the 10- and 20-minutes disruption scenarios, the cancel rate is very low. However, it increases to 6.5% for the worker commuters in the case of a 60 minutes disruption. For student commuters this is almost double at 12.6%.

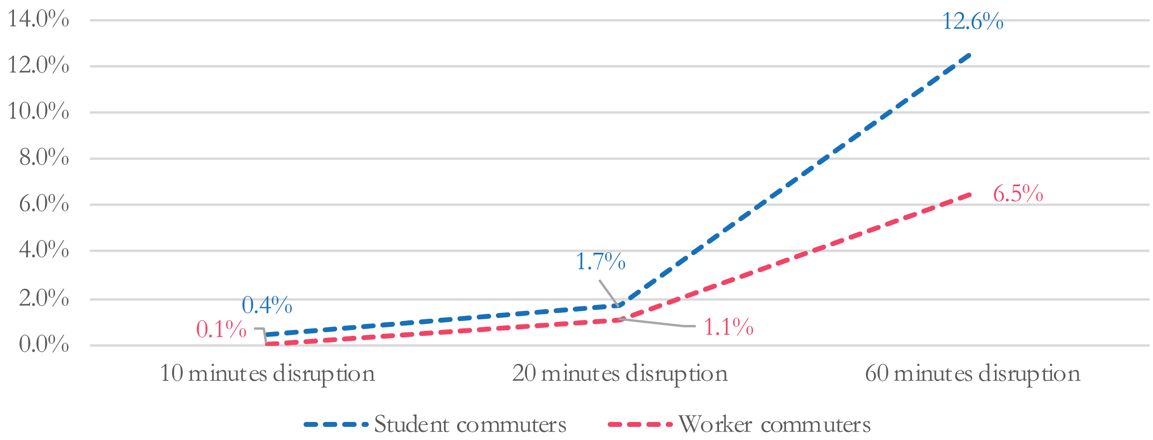


Figure 29 Preference of "Cancel the trip" among different disruption times

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Chapter 6

Model Estimation

After taking a closer look into the survey data in chapter 5, this chapter aims to identify the correlation between dependent variables (preference on replanning behavior) and independent variables (commuters' daily working/studying routine, trip characteristics, and personal attributes). In the model estimation process, a correlation test was conducted on all independent variables. The correlation result is presented in 6.1. The stepwise model developing process is explained in 6.2. 6.3 discusses the interpretation of the coefficients in the final model. 6.4 summarizes the marginal effect of delay time and additional travel cost.

6.1 Correlation tests

The purpose of correlation testing is to identify underlying correlations and avoid collinearity in the model estimation process. This process will assist with the selection of variables during model estimation.

The data collected in this research contain numeric and categorical data. Since the correlation test for numeric and categorical data are different, two correlation tests were implemented:

1. Correlation test on numeric variables

   The only two numerical independent variables are travel time and access time to the first railway stop/station. The Pearson method was used to calculate the correlation between these two variables.

   The Pearson test revealed that travel time and access time have a correlation of 0.53. This means travel time and access time are somehow positively correlated but the correlation value is still within the empirical acceptable range. Regarding model estimation, it is initially assumed that travel time would be more relevant than access time, so travel time will be added.

2. Correlation test on categorical data

The majority of the variables collected in the survey are categorical. All the categorical variables were classified into six groups: personal attributes, daily working/studying routine, commuting trip characteristics, transportation mode and driving license availability, shared mobility subscription, and access mode to the 1st station. The reason for grouping these variables is to offer better visibility when comparing the results.

The Chi test was used to analyze the correlation between categorical variables. The test results are summarized in Table 16 and Table 17. The values in the table are the p-values of the Chi test. This thesis accepts the error of 0.10. If the p-value is lower than 0.10, the null hypothesis (that the two variables are independent) can be rejected. In other words, two variables are correlated if the p-value is lower than 0.10.

From Table 16, the correlation test on the weighted sample reveals high correlations between many variables. For example, all variables in the personal attributes group correlated with each other. This is also the same for the other 5 groups, except for the car driving license and scooter availability. The cross-group correlations are high as well. For example, variables of the personal attributes group correlated with the attributes of the other 5 groups, except for gender and access mode by bike. The correlation pattern is very uncommon, so further investigation was conducted to identify the problem.

After excluding potential coding problems in the statistical software, an additional correlation test was performed on the unweighted data to determine whether the problem was caused by the weighting process. The results of this test are presented in Table 17. These results show a more common pattern compared with empirical studies. In the personal attributes group, all variables are correlated except gender. This is intuitive because worker commuters are usually older than student commuters, have completed their higher education, and have a higher income. Nevertheless, gender and occupation ought to be independent from each other.

Since weighting is an important step in processing survey data, the irregularities in the correlation test of the weighted sample are accepted. Regarding model estimation, having too many correlated variables may reduce the quality of the model. Therefore, the estimation in this thesis introduces only those variables assumed to be most relevant such as occupation and the variables constraining the replanning options (e.g. car availability, carsharing subscription and driving license.)

Table 16 Correlation test on categorical variables of weighted sample

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Personal social economic characteristics																												
1. Occupation	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2. Age	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3. Gender	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00
4. Education	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5. Income	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Daily working or studying routine																												
6. Working hour	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00
7. Core hour	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8. Home office	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Commuting trip characteristics																												
9. Dept Hour	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.65
10. Ticket	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.05	0.01	0.97
11. Information Acq.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transportation mode and driving license availability																												
12. Scooter	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.33	0.00	0.00	0.00
13. Bike	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68	0.00	0.00	0.01	0.00	0.00	0.00
14. Moped	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.23	0.00	0.05	0.00
15. Motorcycle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.26	0.00	0.00	0.01	0.00
16. Car	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17. Car license	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shared mobility subscription																												
18. Scooter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00
19. Bike	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00
20. Motorcycle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21. Car	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.63
Access mode to the 1st railway stop/station																												
22. Walk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00
23. Scooter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
24. Bike	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00
25. Bus	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.30	0.00	0.33	0.01	0.23	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
26. Car	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00
27. Carsharing	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00
28. Tram	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	-

Note: values in the table are the p-values of the Chi test. If the value is lower than 0.10, the null hypothesis can be confidently rejected, which means the two variables are correlated. On the other hand, if the values are higher than 0.10, there is no sufficient evidence to reject the null hypothesis and the two variables are independent.

Table 17 Correlation on categorical variables of unweighted sample

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Personal social economic characteristics																												
1. Occupation	-	0.00	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.09	0.00	0.01	0.01	0.69	0.10	0.00	0.01	0.00
2. Age	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
3. Gender	0.72	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.90	0.00	0.78	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.25	0.00	0.00	0.01	0.09
4. Education	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
5. Income	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Daily working or studying routine																												
6. Working hour	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.04	0.00	0.45	0.00	0.39	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.73	0.01	0.00	0.55	0.02
7. Core hour	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.06	0.00	0.34	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.23	0.14	0.02	0.71
8. Home office	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.01	0.00	0.00	0.00	0.00	0.73	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.03	0.24	0.00	0.14	0.00	0.66
Commuting trip characteristics																												
9. Dept Hour	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.09	0.00	0.00	0.48	0.38
10. Ticket	0.00	0.00	0.84	0.00	0.00	0.04	0.06	0.01	0.00	-	0.00	0.00	0.00	0.29	0.08	0.00	0.83	0.01	0.18	0.00	0.01	0.38	0.00	0.02	0.02	0.00	1.00	0.18
11. Information Acq.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.30	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.06
Transportation mode and driving license availability																												
12. Scooter	0.01	0.00	0.00	0.01	0.00	0.45	0.34	0.00	0.00	0.00	0.30	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.14	0.00	0.00	0.00	0.11	0.95	0.00
13. Bike	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.16	0.48
14. Moped	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.29	0.00	0.00	0.00	-	0.00	0.89	0.04	0.00	0.10	0.00	0.00	0.60	1.00	0.00	0.32	0.12	1.00	0.29
15. Motorcycle	0.12	0.00	0.78	0.00	0.00	0.17	0.02	0.73	0.00	0.08	0.00	0.00	0.84	0.00	-	0.00	0.00	0.09	0.00	0.00	0.05	0.00	0.66	0.03	0.00	0.02	1.00	0.08
16. Car	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.89	0.00	-	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00
17. Car license	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.00	0.00	0.00	0.04	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.10	0.00
Shared mobility subscription																												
18. Scooter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.09	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.90	0.00	0.05
19. Bike	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	-	0.00	0.00	0.27	0.00	0.03	0.08	0.48	0.00	0.34
20. Motorcycle	0.09	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	-	0.00	0.02	0.00	0.43	0.01	0.15	0.00	0.00
21. Car	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.50	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	-	0.00	0.18	0.26	0.79	0.04	0.00	0.55
Access mode to the 1^{st} railway stop/station																												
22. Walk	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.08	0.00	0.38	0.00	0.14	0.00	0.60	0.00	0.00	0.00	0.00	0.27	0.02	0.00	-	0.00	0.00	0.00	0.00	0.27	0.38
23. Scooter	0.01	0.00	0.96	0.00	0.00	0.05	0.02	0.03	0.02	0.00	0.00	0.00	0.00	1.00	0.66	0.00	0.59	0.00	0.00	0.00	0.18	0.00	-	0.00	0.99	0.00	0.00	0.00
24. Bike	0.69	0.00	0.25	0.00	0.00	0.73	0.00	0.24	0.09	0.02	0.05	0.00	0.00	0.00	0.03	0.00	0.00	0.44	0.03	0.43	0.26	0.00	0.00	-	0.83	0.00	0.38	0.00
25. Bus	0.10	0.00	0.00	0.00	0.00	0.01	0.23	0.00	0.00	0.02	0.00	0.00	0.03	0.32	0.00	0.28	0.00	0.00	0.08	0.01	0.79	0.00	0.99	0.83	-	0.07	0.00	0.45
26. Car	0.00	0.01	0.00	0.00	0.00	0.00	0.14	0.14	0.00	0.00	0.00	0.11	0.00	0.12	0.02	0.00	0.00	0.90	0.48	0.15	0.04	0.00	0.00	0.00	0.07	-	0.00	0.00
27. Carsharing	0.01	0.00	0.01	0.00	0.00	0.55	0.02	0.00	0.48	1.00	0.00	0.95	0.16	1.00	1.00	0.00	0.10	0.00	0.00	0.00	0.00	0.27	0.00	0.38	0.00	0.00	-	0.00
28. Tram	0.00	0.00	0.09	0.03	0.00	0.02	0.71	0.66	0.38	0.18	0.06	0.00	0.48	0.29	0.08	0.00	0.00	0.05	0.34	0.00	0.55	0.38	0.00	0.00	0.45	0.00	0.00	-

Note: values in the table are the p-values of the Chi test. If the value is lower than 0.10, the null hypothesis can be confidently rejected, which means the two variables are correlated. On the other hand, if the values are higher than 0.10, there is no sufficient evidence to reject the null hypothesis and the two variables are independent.

6.2 Model development

The model development process follows an incremental additive method in which variables are added one by one. This stepwise method allows for better control during the model development process. This section describes how this process was applied in the development of the final model. This section does not discuss the values of the coefficients in detail but instead focuses on the sign of coefficients and their changes between steps. Coefficients are then interpreted carefully in section 6.3.

1. Base model

   When designing the SC experiment, orthogonal experimental design method was applied. Since orthogonal experimental design requires predefined model form, the first model (base model) was estimated as what we defined during the experimental design. The base model helps us to justify whether the experimental design is effective. The result of base model is shown in Table 18.

   The base model includes alternative specific constants (ASCs), delay time and additional cost. "Stay & wait" is the reference alternative, so its ASC is zero. The ASCs of other alternatives are compared against it. It is worth pointing out that the ASC of "Use Carsharing", "Other", and "Cancel" are relatively large. This means the variables introduced so far do not explain the choice that much. More variables should be introduced to enhance the fitting power.

   Additional cost is considered as an alternative generic variable and delay time is considered as an alternative specific variable. Parameters of both these variables have negative signs. These negative signs meet our expectation because cost and time are perceived as impedance. When delay time and additional travel cost increase, replanning options become less attractive. In addition, all the parameters are significant, and the base model has the Rho-square of 0.51. We can conclude that the experimental design is effective and leads to an effective base model.

2. Effects of adding disruption duration

   Recap the research question of this thesis: "To what extent does the duration of service disruption correlate with the rapid rail commuters' short-term en-route replanning behavior?" From the research question, the main investigating item in this thesis is to see whether the duration of service disruptions influence commuters' replanning behavior, so three scenarios were created in the SC experiment, which are 10-, 20-, and 60-minutes delay. Hence, the variable of disruption scenarios was introduced to the base model to see how the disruption duration affects the model.

The estimation result is shown in Table 19. The result shows that the coefficients' sign of ASCs, additional travel cost, and delay time remain the same. The disruption scenario variable is introduced as a dummy variable and the reference level is 10-minutes delay. The 20- and 60-minutes delay scenarios are compared against the reference scenario. From SC20 and SC60, the signs of "Stay & wait" are negative, which means "Stay & wait" is perceived less attractive when the disruption is 20- or 60-minutes than 10-minutes. The other alternatives hold positive coefficients, except for the SC20 of "Use another PT line". However, this parameter is insignificant, which means the parameter is not different from zero.

Based on the result of this model, the research question can be partly answered. Commuters tend not to "Stay & wait" and prefer to re-plan their trip when disruption increases. However, this finding is maybe not sufficient, so interaction term of additional travel cost and disruption scenario and interaction term of delay time and disruption scenario were added.

3. Interaction effects

The base model with interaction effects is shown in Table 20. The signs of the coefficients from the previous model have changed because of the introduction of interaction terms. Here, we focus on the additional cost, delay time, and their interactions with SC20 and 60. The coefficient of additional cost remains negative, but the coefficients of additional cost and disruption scenario interaction terms are positive. This means that commuters perceive cost less negative when the disruption duration climbs up.

As to delay time, the coefficient of "Stay & wait" becomes positive. This does not mean that commuters perceive delay in "Stay & wait" positively under the 10-minutes scenario, but rather a compared perception. The delay time and disruption scenario interaction terms show reasonable signs. The interaction term for "Stay & wait" are negative, which means less attractive. The coefficients of other alternatives are positive, which is means less negative compared with the 10-minutes delay.

This model shows an interesting finding that commuters perceive additional cost and delay time differently under different disruption durations. This finding also adds answers to the research question of this thesis.

4. Effects of other variables

After systematically extending the model in steps 1 – 3, there are still some relevant variables that have not yet been included. In this step, other variables collected in the survey are added by considering the correlation test results from the previous section. Variables added during this step are travel time, occupation (student as reference level), car & driving license (binary), and carsharing & driving license (binary). The estimation result is shown in Table 21.

.

Table 18 Estimation result of base model

Choice	Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Alternative Specific Constant (ASC)	-	-1.33*** [-55.80]	-2.86*** [-60.70]	-4.35*** [-64.90]	-2.57*** [-11.90]	-4.44*** [-161.00]	-4.96*** [-158.00]
Additional Cost (C)			-0.21*** [-33.70]			-	-
Delay time (D)	-0.10*** [-95.20]	-0.08*** [-68.60]	-0.04*** [-30.20]	-0.06*** [-16.00]	-0.06*** [-5.27]	-	-
Initial log likelihood: -113222.80			Final log likelihood: -55843.68			Rho-square: 0.51	

Note: value in the table represents the estimated coefficient, t-test statistic is in the bracket, and significance is marked by * (p-value < 0.10), ** (p-value< 0.05), and *** (p-value< 0.01).

Table 19 Estimation result of base model with disruption effect

Choice	Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Alternative Specific Constant (ASC)	-	-0.88*** [-37.90]	-2.72*** [-41.60]	-3.67*** [-33.30]	-2.40*** [-6.35]	-4.18*** [-68.00]	-6.40*** [-35.10]
Additional Cost (C)			-0.21*** [-33.60]			-	-
Delay time (D)	-0.02*** [-12.80]	-0.09*** [-67.60]	-0.04*** [-30.10]	-0.06*** [-16.00]	-0.06*** [-5.25]	-	-
20 minutes disruption (SC20)	-1.72*** [-26.10]	-0.01 [-0.05]	0.44*** [5.30]	-0.52*** [-4.26]	0.53* [1.69]	0.34*** [4.03]	0.94*** [5.39]
60 minutes disruption (SC60)	-3.71*** [-47.10]	0.17*** [2.70]	0.43*** [5.3400]	0.02 [0.22]	0.31 [0.98]	0.28*** [3.43]	2.49*** [14.80]
Initial log likelihood: -113222.80			Final log likelihood: -54379.14			Rho-square: 0.52	

Note: value in the table represents the estimated coefficient, t-test statistic is in the bracket, and significance is marked by * (p-value < 0.10), ** (p-value< 0.05), and *** (p-value< 0.01).

Table 20 Estimation result of base model and disruption interaction

Choice	Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Alternative Specific Constant (ASC)	- -	2.60*** [1.00]	1.16*** [0.45]	0.46*** [0.18]	0.45 [0.03]	-1.26*** [-0.48]	-3.48*** [-1.33]
Additional Cost (C)			-0.41*** [-22.50]			-	-
C*SC20			0.17*** [8.25]			-	-
C*SC60			0.26*** [13.20]			-	-
Delay time (D)	0.28*** [1.06]	-0.16*** [-40.80]	-0.07*** [-11.50]	-0.08*** [-6.27]	-0.40*** [-0.38]	-	-
D*SC20	-0.23*** [-0.89]	0.06*** [13.50]	0.03*** [3.66]	0.00 [-0.23]	0.34*** [0.32]	-	-
D*SC60	-0.30*** [-1.15]	0.12*** [27.30]	0.04*** [5.82]	0.03** [2.15]	0.35*** [0.33]	-	-
20 minutes disruption (SC20)	-0.01*** [-0.89]	-0.39*** [-0.15]	-0.39*** [-0.15]	-1.72*** [-0.66]	1.24** [0.10]	0.33* [0.13]	0.94*** [0.36]
60 minutes disruption (SC60)	-0.01*** [-1.15]	-0.63*** [-0.24]	-0.61*** [-0.23]	-1.31*** [-0.50]	-0.86* [-0.07]	0.60*** [0.23]	2.8*** [1.07]
Initial log likelihood: -113222.80			Final log likelihood: -53720.88			Rho-square: 0.53	

Note: value in the table represents the estimated coefficient, t-test statistic is in the bracket, and significance is marked by * (p-value < 0.10), ** (p-value< 0.05), and *** (p-value< 0.01).

Table 21 Estimation result of base model with disruption interaction effect and other variables

Choice	Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Alternative Specific Constant (ASC)	-	2.94*** [0.77]	-2.49*** [-0.65]	-0.18 [-0.05]	2.04*** [0.11]	0.88*** [0.23]	-3.23*** [-0.84]
Additional Cost (C)			-0.42*** [-22.80]			-	-
C*SC20			0.16*** [7.45]			-	-
C*SC60			0.25*** [12.00]			-	-
Delay time (D)	0.22*** [0.56]	-0.16*** [-40.70]	-0.07*** [-11.40]	-0.08*** [-6.64]	-0.42*** [-0.27]	-	-
D*SC20	-0.22*** [-0.57]	0.06*** [13.00]	0.02*** [2.65]	-0.00 [-0.22]	0.37*** [0.24]	-	-
D*SC60	-0.26*** [-0.67]	0.12*** [26.60]	0.03*** [4.45]	0.03** [2.06]	0.38*** [0.25]	-	-
20 minutes disruption (SC20)	-0.01*** [-0.57]	-0.60*** [-0.16]	-0.51*** [-0.13]	-1.70*** [-0.44]	1.98*** [0.10]	0.20 [0.05]	0.64*** [0.17]
60 minutes disruption (SC60)	-0.01*** [-0.67]	-0.91*** [-0.24]	-0.81*** [-0.21]	-1.16*** [-0.30]	0.00 [0.00]	0.49*** [0.13]	2.39*** [0.62]
Travel time	0.03*** [25.70]	0.01*** [8.50]	0.03*** [22.90]	-0.02*** [-8.11]	-0.04*** [-6.22]	-0.04*** [-20.30]	0.02*** [14.20]
Occupation	-0.18*** [-3.69]	-0.18*** [-3.82]	0.88*** [11.20]	1.30*** [8.81]	-0.49** [-2.43]	-0.44*** [-7.80]	-0.90*** [-14.40]
Car & Driving license	-0.64*** [-15.10]	-0.55*** [-14.10]	2.24*** [34.00]	-1.00*** [-11.80]	1.02*** [5.32]	-0.89*** [-17.20]	-0.19*** [-3.21]
Carsharing & Driving license	0.12*** [0.31]	0.51*** [1.35]	0.38*** [0.99]	2.90*** [7.52]	-4.92*** [-2.17]	1.05*** [2.78]	-0.04 [-0.10]
Initial log likelihood: -113222.80			Final log likelihood: -48361.80			Rho-square: 0.57	

Note: value in the table represents the estimated coefficient, t-test statistic is in the bracket, and significance is marked by * (p-value < 0.10), ** (p-value< 0.05), and *** (p-value< 0.01).

Table 22 Estimation result of final model

Choice	Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Alternative Specific Constant (ASC)	-	2.56*** [27.40]	-2.86*** [-24.40]	-0.54*** [-2.61]	2.72*** [7.94]	1.45*** [13.60]	-3.38*** [-18.30]
Additional Cost (C)			-0.36*** [-27.80]			-	-
C*SC20			0.10*** [6.09]			-	-
C*SC60			0.17*** [14.30]			-	-
Delay time (D)	0.21*** [20.60]	-0.14*** [-39.00]	-0.07*** [-12.40]	-0.07*** [-17.30]	-0.28*** [-8.66]	-	-
D*SC20	-0.19*** [-32.70]	0.04*** [9.08]	0.01** [2.31]	-	0.23*** [6.26]	-	-
D*SC60	-0.24*** [-28.60]	0.08*** [21.90]	0.03*** [4.45]	-	0.24*** [7.65]	-	-
20 minutes disruption (SC20)	-0.01*** [-32.70]	0.19*** [3.88]	0.27** [2.64]	-0.78*** [-4.47]	1.64*** [3.63]	-	1.19*** [5.98]
60 minutes disruption (SC60)	-0.01*** [-28.6]	-	-	-0.42*** [-3.02]	-	-	2.86*** [15.20]
Travel time	0.03*** [25.10]	0.01*** [8.17]	0.03*** [22.70]	-0.02*** [-8.20]	-0.04*** [-6.12]	-0.03*** [-19.50]	0.02*** [14.10]
Occupation	-0.19*** [-3.92]	-0.18*** [-3.82]	0.88*** [11.20]	1.32*** [8.90]	-0.50** [-2.46]	-0.44*** [-7.78]	-0.90*** [-14.40]
Car*Driving license	-0.65*** [-15.40]	-0.56*** [-14.10]	2.25*** [34.00]	-1.00*** [-11.80]	1.05*** [5.45]	-0.91*** [-17.50]	-0.18*** [-3.10]
Carsharing*Driving license	-0.88*** [-17.60]	-0.51*** [-10.80]	-0.64*** [-9.60]	1.89*** [19.20]	-5.86*** [-2.30]	-	-1.07*** [-11.40]
Initial log likelihood: -113222.80			Final log likelihood: -48368.60			Rho-square: 0.57	

Note: value in the table represents the estimated coefficient, t-test statistic is in the bracket, and significance is marked by * (p-value < 0.10), ** (p-value< 0.05), and *** (p-value< 0.01).

From Table 21, the parameters estimated in previous steps keep the same signs. The travel time variables have positive signs for “Stay & wait”, “Use another PT line”, “Use my own car”, and “Cancel the trip”. This shows that commuters with longer travel times tend to choose these four options. These options are considered cheaper than “Use carsharing” and “Take taxi”. Since the “Other” option includes walk and bike, it is understandable that commuters wouldn’t choose to bike or walk if their destination is far away.

Regarding the worker variable, the reference level is student and the signs of most alternatives are negative except for “Use my own car” and “Use carsharing”. This shows that compared with student commuters, worker commuters would prefer to drive their car or use carsharing. One thing which is not intuitive is the parameters of “Take taxi”. The sign is negative, which suggests that student commuters prefer this option more than workers. However, common sense tells us that employees have higher incomes than students, so this mode is more affordable to worker commuters. This negative value is a result of more student respondents choosing to “Take taxi” than worker respondents in the survey.

The last two dummy variables Car & Driving license and Carsharing & Driving license have positive signs on “Use my own car” and “Use carsharing” respectively. This means that people having car available for use and possessing driving license tend to choose “Use my own car”. Commuters having carsharing membership and possessing driving license prefer “Use carsharing”.

At this step, the Rho-square of this model is 0.57 and the signs make sense, except for the occupation dummy variable on the taxi alternative. The remaining steps of the model development process drop the variables determined to be insignificant. The confidence level chosen in this research is 0.10. Variables with the p-value greater than 0.10 are removed gradually to obtain the final model.

6.3 Interpretation on the final model

This section gives a comprehensive review of the final model, which is summarized in Table 22. The final review discusses the signs and values of coefficients and compares the values across alternatives and between interaction terms.

1. Alternative specific constant

   The absolute value of all ASCs in the final model have decreased compared with the base model. This indicates that adding variables provided more explanatory power. Nevertheless, the option “Cancel the trip” still has the largest ASC, meaning this option is the least well explained.

2. Additional cost and interaction terms with disruption scenario

   The 'additional cost' coefficient has a value of -0.36, which means one euro increase in additional travel cost corresponds with a utility decrease of 0.36. The utility increases by 0.10 and 0.17 in the 20- and 60-minutes disruption scenarios respectively, but the overall effect of additional travel cost remains negative. This overall effect is -0.26 for the 20-minutes scenario and -0.19 for the 60-minutes scenario.

3. Delay time and interaction terms with disruption scenario

   From the parameters of delay time, "Take taxi" is the least preferable option under the 10-minutes scenario because it has the largest negative value (-0.28). However, this option becomes more attractive in the 20- and 60-minutes scenarios. The interaction term of delay time and disruption scenario (D*SC20 and D*SC60) shows that the utility of taxi increases by 0.23 and 0.24 respectively. Interaction terms for other alternatives have a similar effect, such as "Use another PT line" and "Use my own car". The interaction terms for a 60-minutes delay are all larger than those for a 20-minutes delay, suggesting that a 60-minutes delay has a greater effect on replanning decisions. Nevertheless, the interaction effect works differently for "Stay & wait", where the D*SC20 and D*SC60 are both negative but D*SC60 is more negative than D*SC20. This indicates that delay time for "Stay & wait" is perceived more negative when the disruption time is longer.

4. Disruption scenario

   The parameters of this variable have changed significantly since they were first introduced. SC20 has positive effect on "Use another PT line", "Use my own car", "Take taxi", and "Cancel the trip" and negative effective on the others. The option "Cancel the trip" has the value of 1.18, which shows that the variable of SC20 increases the probability of this option. For SC60, many parameters become insignificant compared with the 10 minutes scenario. But still, "Stay & wait" and "Use carsharing" become less preferable while "Cancel the trip" becomes more preferable. We can conclude that the dummy of disruption scenario helps to catch the effects on "Cancel the trip".

5. Other variables

   Travel time, occupation, and Car & Driving License remain mostly the same, so the review of these three variables is skipped. However, the effects of Carsharing & Driving license change substantially. In the previous model, Carsharing & Driving license had a positive effect on all alternatives except "Take taxi". In this model, the variable only has positive effect on" Use carsharing", which is more reasonable. Also, this variable has the strongest negative effect on taxi, suggesting that commuters having carsharing membership are very unlikely to take taxi.

6.4 Marginal effects

This section presents the marginal effect of delay time and additional travel cost, which can provide a clear look at the impacts when values of these two variables change. The discussion focuses on the marginal effects of PT's delay time and additional cost because this is our key interest. The other alternatives' marginal effects are summarized in Table 23, Table 24, and Table 25.

Figure 30 shows the change in probability if one minutes delay increases in the PT option. In scenario 10, "Stay & wait" is the most competing option and increases by 0.012 when PT delays one more minute. Under the scenario 20, "Stay & wait" is not the best option anymore, but "Use carsharing" and "Other". In the scenario 60, the marginal decrease of PT (-0.013) is smaller than the previous options.

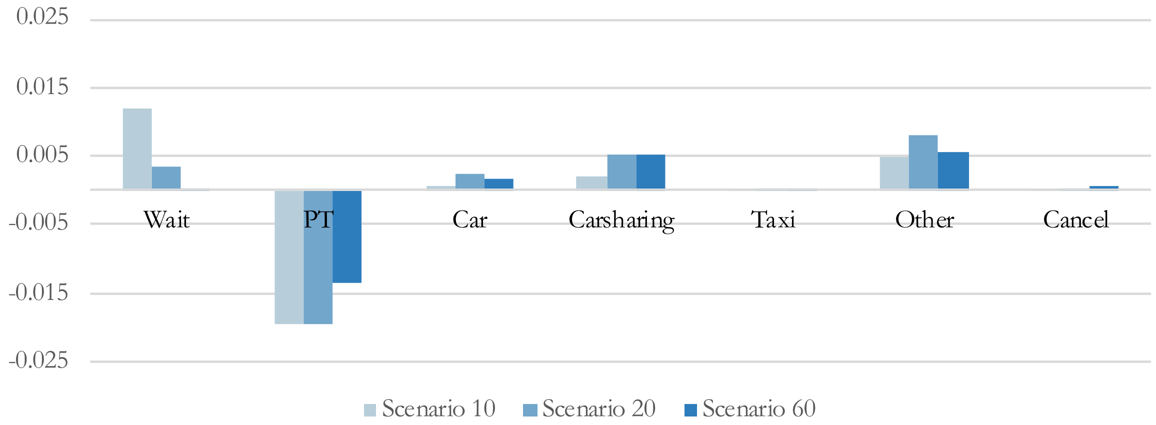

Figure 30 Marginal effect of delay time on PT

Figure 31 shows the marginal effect of PT's additional cost, and it shows that the marginal effect of PT's additional cost has similar pattern as delay time, but the additional cost has larger value.

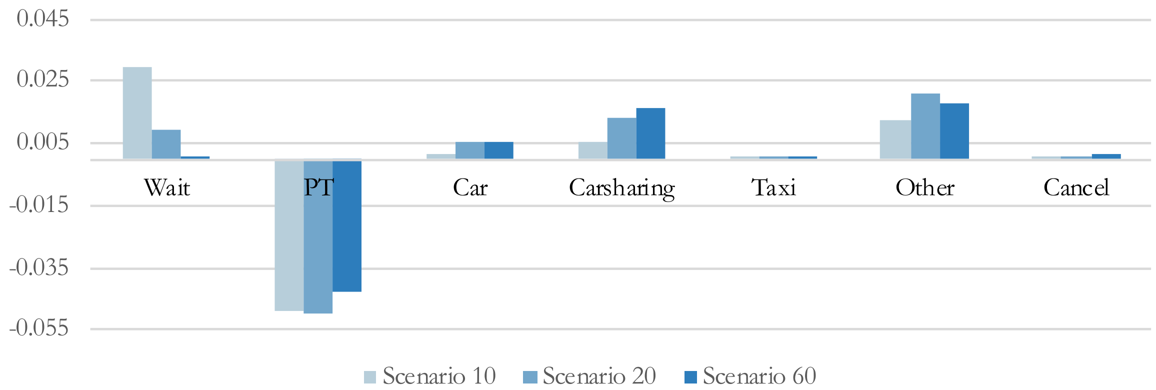

Figure 31 Marginal effect of additional travel cost on PT

Table 23 Marginal effects of additional travel cost and delay time in scenario 10

Attributes		Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Additional travel cost	PT	0.012	-0.020	0.001	0.002	0.000	0.005	0.000
	Car	0.001	0.000	-0.002	0.000	0.000	0.000	0.000
	Carsharing	0.006	0.002	0.000	-0.011	0.000	0.002	0.000
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Delay time	PT	0.030	-0.049	0.002	0.005	0.000	0.012	0.000
	Car	0.004	0.001	-0.007	0.001	0.000	0.001	0.000
	Carsharing	0.015	0.005	0.001	-0.027	0.000	0.006	0.000
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 24 Marginal effects of additional travel cost and delay time in scenario 20

Attributes		Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Additional travel cost	PT	0.004	-0.019	0.002	0.005	0.000	0.008	0.000
	Car	0.000	0.001	-0.003	0.001	0.000	0.001	0.000
	Carsharing	0.002	0.005	0.001	-0.012	0.000	0.004	0.000
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Delay time	PT	0.009	-0.050	0.006	0.014	0.000	0.021	0.000
	Car	0.002	0.005	-0.013	0.003	0.000	0.004	0.000
	Carsharing	0.004	0.013	0.003	-0.030	0.000	0.009	0.000
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 25 Marginal effects of additional travel cost and delay time in scenario 60

Attributes		Wait	PT	Car	Carsharing	Taxi	Other	Cancel
Additional travel cost	PT	0.000	-0.013	0.002	0.005	0.000	0.006	0.001
	Car	0.000	0.001	-0.002	0.001	0.000	0.001	0.000
	Carsharing	0.000	0.005	0.001	-0.009	0.000	0.002	0.000
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Delay time	PT	0.001	-0.042	0.006	0.016	0.000	0.018	0.002
	Car	0.000	0.005	-0.010	0.002	0.000	0.002	0.000
	Carsharing	0.000	0.016	0.002	-0.027	0.000	0.008	0.001
	Taxi	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Chapter 7

Case Study

The previous chapter described and evaluated the estimated en-route replanning model theoretically. This chapter looks at the applicability and the performance of the estimated model with a case study. The case study is done by inputting travel demand data from MITO and using MATSim for assignment. In the following paragraphs, the case study scenario is presented in 7.1. Input demand data and preparation work for the case study are explained in 7.2. 7.3 provides the analysis results of the case study.

7.1 Disruption scenario

According to the statistic of the service disruptions in Chapter 3, there are many show cases of service disruption in the study area. However, the disruption scenario of this case study is based on the latest massive interruption in the U-Bahn system in the City of Munich. On the 29th of October 2019, a train operating on the U7 line derailed causing a massive service disruption (Süddeutsche Zeitung, 2019). Stations between Kolumbusplatz and Hauptbahnhof of the U1/2 lines were interrupted for the whole evening till next day.

The case study is not aiming for rebuilding or backcasting the situation at that moment but simulating a simplified situation for testing the applicability of the model. This thesis chooses to simulate the disruption on the same section (Kolumbusplatz - Haupfbahnhof) but with bidirectional blockage. Three scenarios of the disruption duration were introduced, which are 10-, 20-, and 60-minutes blockages. The disruptions all start from 8 o'clock and their durations depend on the scenario. The transit schedule was modified by removing the transit vehicles when they enter the blocked section during the disruption time. As Figure 32 shows, the X-axis is the sequence of stations and the Y-axis is the time. Green solid lines represent each vehicle run from the origin station to the destination station. The red line represents the trajectory of affected vehicles, which shows vehicles stopping at the first blocked station. The number of affected services is summarized in Table 26. In this scenario, supplementary shuttle services are not considered in the case study.

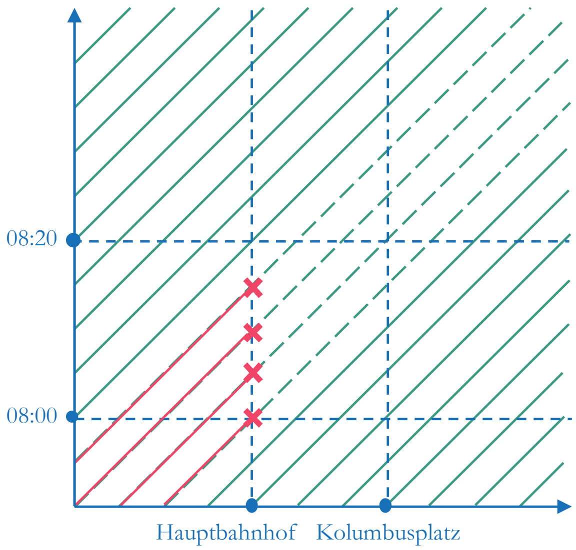

Figure 32 Demonstration of interruption setting

Table 26 Number of affected services of each line

Transit routes	Scenario 10	Scenario 20	Scenario 60
U1: Oly.-EKZ. - Mangfallplatz	2	4	12
U1: Mangfallplatz – Oly.-EKZ.	2	4	12
U2: Feldmoching – Messestadt Ost	2	4	12
U2: Messestadt Ost - Feldmoching	2	4	12

In addition to defining these disruption scenarios, some additional model parameters not included in MITO or MATSim need to be approximated. These are parking searching time, access time to carsharing, waiting time for taxi, and parking fee. These parameters are listed in Table 27 and explained below.

1. Parking searching time and parking fee

   The parking searching time was approximated to be 3 or 6 minutes depending on commuters' destination. If commuters' destination is located within the Mittlerer Ring, the parking searching time is 6 minutes and the parking fee is 6 euro per day. If commuters' destination located outside of the Mittlerer Ring, the parking searching time is 3 minutes with no parking fee because there is usually no parking management in the outskirts of the city.

2. Access time to carsharing

   The access time to carsharing is approximated by the business area of Drive Now. If the station, where commuters encounter the disruption, is located within DriveNow's business area, the access time defaults to 5 minutes. If the station is outside of Drive Now's operating area, the value is set to 10 minutes.

3. Waiting time for taxi

   The waiting time for taxi is approximated by the location of the taxi stand. If there is a taxi stand near the U-Bahn station, the waiting time is 5 minutes. If not, we assume commuters need to make a phone call and wait for the taxi, which might take up to 10 minutes.

Table 27 Predefined parameters of car related replanning options

Parameters	Value
Parking searching time	3 or 6 minutes
Parking fee	0 or 6 euros
Access time to carsharing	5 or 10 minutes
Waiting time for taxi	5 or 10 minutes

7.2 Demand data

The demand data was obtained from the MITO model, which is a full population with 6,640,967 agents. To reduce the model run time, agent size was reduced by removing agents whose 1st departure is after 11 o'clock. After the agent size reduction, there are 2,252,705 agents whose first departure is during the morning hour and 175,996 of them use PT in their trip. However, this thesis focus on the commuters, so the agent size was further reduced to only include those carrying out home-based work and home-based education trips, which are 92,372 commuters. The statistics are summarized in Table 28.

Table 28 Statistics of trip data

Statistics	Values
Total agents	6,640,967
Agents departing in the morning hour	2,252,705
PT agents departing in the morning hour	175,996
PT commuters departing in the morning hour	92,372

The demand data does not provide any information about the routes that commuters choose, so the demand data was inputted into MATSim for assignment. In this thesis, PT commuters were assigned on the PT network, but the network is not integrated with the road traffic, which means road traffic does not impact the travel time of some PT systems such as bus and tram. However, the case study focusses mainly on the rapid rail system, so we assume these effects can be neglected. The assignment result is not validated with passenger count data because no data is available and that is not the core part of this thesis. Therefore, the results of this case study can help us to understand relative changes, but any interpretation or translation of absolute numbers should be treated carefully.

After the assignment, a java class was developed to identify affected commuters. As Table 29 shows, around 386 passengers encounter the service disruption in scenario 10, of which 241 commuters experience the disruption when they enter the stations and 145 commuters experience the disruption on board. In the scenario 20, the total affected passengers increase by 90.9%, but the increase is higher for commuters affected on board than for commuters affected en-route. In the worst-case (60 minute) scenario, the total affected commuters increase by 132.7% compared with scenario 20. In this scenario, the increase is greater for en-route commuters than for on board commuters. These results show that the growth of the affected commuters by scenarios is not linear, which might influence our analysis of the case study.

Table 29 Statistics of affected passengers in different scenarios

Number of affected agents	Scenario 10	Scenario 20		Scenario 60	
En-route affected	241	437	(+81.3%)	1,021	(+133.6%)
On board affected	145	300	(+106.9%)	694	(+131.3%)
Total affected	386	737	(+90.9%)	1,715	(+132.7%)

Note: en-route affected means that commuters encounter the disruption when they arrive at the station. On board affected means that the passenger encounters the disruption in the vehicle.

To capture the dynamic pattern of passengers' arrival, Table 30 shows the number of affected commuters and their experienced disruption time by scenario. Commuters' experienced disruption time is calculated by deducting commuters' arrival time at the PT station from the expected arrival time of next PT service, which can be understood as the delay time for "Stay & wait".

As the table shows, all commuters are affected for 10 minutes in the scenario 10. In the scenario 20, not everyone is affected by 20 minutes because some of them arrive at the station shortly before the disruption is overcome. In this case 391 of them encounter 10~20 minutes disruption, and the other 346 face 10-minutes disruption. However, the commuters facing 10-minutes disruption becomes less. In the scenario 60, only 186 are arrived at the station and experienced 10 minutes disruption. This finding is very important because the model is dependent on the disruption time that people experience. The input number influences the overall analyzing results.

Table 30 Affected disruption time of commuters in different scenarios

Affected time	Scenario 10	Scenario 20	Scenario 60
Less than and equal 10	386	346	186
10~20 minutes	-	391	210
20~60 minutes	-	-	1,319

7.3 Replanning analysis

After the affected commuters are identified, another java class was developed to calculate the delay time and additional travel cost of each replanning options. These two attributes are the input for the replanning model. The following paragraphs presents the share of replanning options and the diagnose of the model application.

1. Share of replanning options

   The en-route trip replanning results are summarized in Table 31. In scenario 10, 52.3% of the commuters choose "Use another PT line" and 44.6% of them choose "Stay & wait". There are only 3.1% of the commuters choose car mode: 0.5% car and 2.6% carsharing.

   In the scenario 20, the share of "Use another PT line" increases to 74.5% and "Stay & wait" drops significantly to half (21.0%) compared with the scenario 10. Nevertheless, the share of car related option rises very slightly to 3.0%: car 0.9%, carsharing 2.0%, and taxi 0.1%. Additionally, 1.4% of the affected commuters decide to walk or bike to destination.

   In the scenario 60, the share of "Use another PT line" increases up to 90.2%. "Stay & wait" decreases to 4.9%. "Use my own car" and "Other" grows continuously to 2.0% and 2.1% respectively. Carsharing and taxi remains minority but very few commuters do cancel their trip in response to this massive disruption.

   From the table, the substitution effect between "Stay & wait" and "Use another PT line" can be clearly observed. However, the increases of car mode are not obvious. This trend is somehow against our common understanding.

Table 31 Share of replanning decisions in different scenarios

Replanning options	Scenario 10		Scenario 20		Scenario 60	
Stay & wait	172	(44.6%)	155	(21.0%)	84	(4.9%)
Use another PT line	202	(52.3%)	549	(74.5%)	1547	(90.2%)
Use my own car	2	(0.5%)	7	(0.9%)	34	(2.0%)
Use carsharing	10	(2.6%)	15	(2.0%)	10	(0.6%)
Take taxi	0	(0.0%)	1	(0.1%)	1	(0.1%)
Other	0	(0.0%)	10	(1.4%)	36	(2.1%)
Cancel the trip	0	(0.0%)	0	(0.0%)	3	(0.2%)

2. Diagnose of model applicability

   From previous paragraph, an unexpected analysis result was identified. This paragraph found the hiding reasons of the unexpected results. Since the main acting variables in the trip replanning model is delay time and travel cost, the delay time distribution and additional travel cost distribution are plotted for clarifying the suspected problem in the model. Since the scenario

60 has the most extreme value, the following two plots are obtained from this scenario and shown in Figure 33 and Figure 34.

From Figure 33, it can be clearly observed that the delay time of car is way too high than expectation. The average delay of car mode is 55.4 minutes, while the delay time of wait, PT, carsharing, and taxi are 50.0, 7.34, -5.0, and -9.36 respectively. This is the evidence showing why the car share is so low after replanning. Besides, the delay time setting is almost consistent with the model results, except for “Use my own car”.

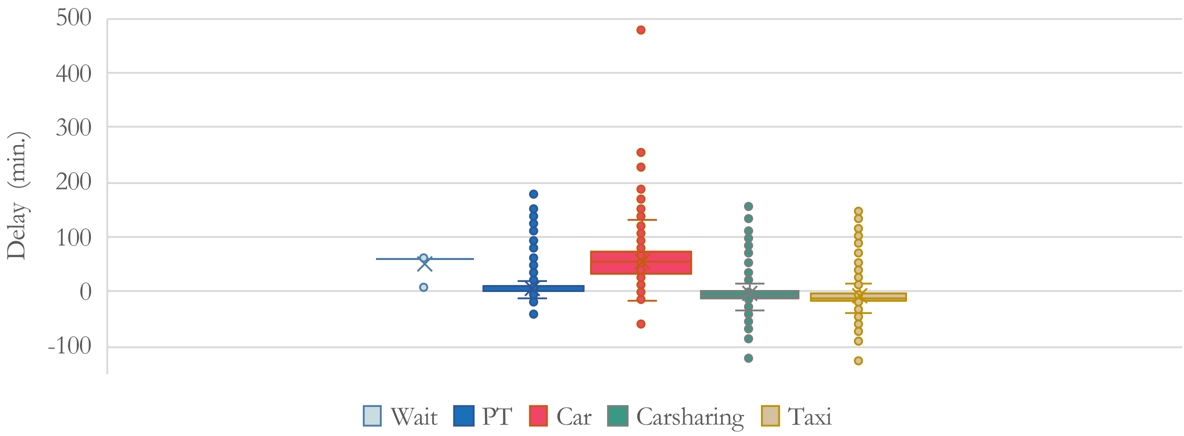

Figure 33 Distribution of delay time

Figure 34 shows the distribution of additional travel cost of each alternative. The average travel cost of PT, car, carsharing, and taxi are 0.4, 5.9, 3.5, and 21.0 euro. Compared with the value in SC experiment, the costs of car related mode are overestimated in the SC experiment. The costs of the car related mode derived from the model are lower than the SC settings.

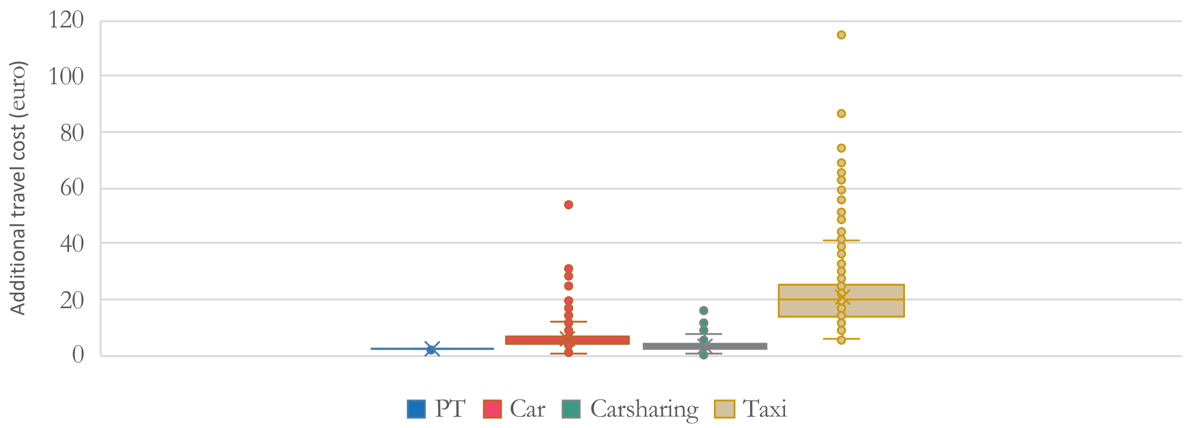

Figure 34 Distribution of additional travel cost

Chapter 8

Discussion & Conclusion

This is the last chapter of this thesis. The discussion on main findings, conclusion, limitation, and recommendation on further works are addressed in this chapter.

8.1 Discussion on main findings

1. Status quo investigation

   In the interview, MVG shared lots of valuable information to the author, especially the causes to service disruption. Compared with the study of Lin et al. (2016), both study identify similar major causes of service disruption. From the data collected on MVG's and DB's websites, the top 2 common causes of service disruption are operation reason and technical problem In the research of Lin et al. (2016), the top 2 causes in Toronto City subway are human accidental (medical service or crew availability issues) and human operating environment (technical problem). However, one difference is that MVG clams no strong association between the causes and disruption duration, while Lin et al. (2016) claimed the association in their study.

2. Survey data analysis

   In the survey data, most of the variable distribution is within our expectation, such as the ticket used by commuters and the daily working/studying hour by occupation. However, there are 2 findings, which are beyond our expectation. The first one is core working/studying hour. Only 37.1% of the worker commuters have core hour, but 66.5% of the students have core hour. The second special finding is the frequency of information acquisition before departure. Around 26.2% of the worker commuters never check the operation status before leaving their house, while only 10.4% of the student commuters never check the status.

3. Model estimation

The model of this thesis shows that additional travel cost become less negative as disruption time increases, and delay time of "do replanning options" also become less negative as duration time increases. In addition, "Cancel the trip" has the most negative alternative specific constant. This is similar to the study of Lin et al., (2018). The "Cancel" alternative also has the most negative value, which shows that this option is the least preferable and not fully described by other variables. In the study of Nguyen-Phuoc et al. (2018b), the "Cancel the trip" option is also included. Their findings are consistent with this research. Car ownership, driving license possession, and the travel time have negative influence on choosing "Cancel"

4. Case study

The case study found a very strong substitute effect between "Stay & wait" and "Use my own car". However, the share of "Use my own car" is very low. Through the diagnose on the model, the problem is the long delay time in car mode. Via a further investigation, the long delay time is dominated by the long access time from the first railway station/stop back to home for using the car, which is 18.7 minutes in average. According to our survey, the average access time is roughly 5 minutes. The PT assignment issue needs to be handled before any further analysis moves forward.

8.2 Conclusion

To the research question "To what extent does the duration of service disruption correlate with the rapid rail commuters' short-term en-route replanning behavior?" This thesis found out that the delay time and scenario interaction terms are statistically significant for most of the replanning alternatives, except for "Other". This option is more correlated with travel time, which is quite relevant for walk and bike, and "Other" stands exactly for these two modes.

As to the correlation between disruption duration and replanning alternative, the share of "Stay & wait" decreases when disruption is longer. The other "do replanning" alternatives increase instead. The reason for this trend is that the coefficient of cost keeps decreasing when disruption becomes longer. Also, the delay time coefficients of "do replanning" alternative increases as disruption duration arises. With these two effects, "Stay & wait" becomes less preferable when disruption goes severe. Among all the "do replanning" options, "Take taxi" has the least utility in the scenario 10, but it becomes more positive as the disruption duration increases. Apart from the delay time and additional travel cost, travel time, occupation, car availability, carsharing membership, and driving license also correlated with the replanning options.

The case study is unfortunately not ready for further analysis yet because the validation needs to be accomplished first. However, the model seems work fine because the delay time and additional travel cost distribution are consistent with the SC experiment design of this research.

8.3 Limitation

The main limitation in this thesis is that all commuters can receive disruption information when they enter stations. This assumption is true for the commuters in the U-Bahn system but not totally true for the S-Bahn commuters. Most of the underground stations and transfer stations of S-Bahn are equipped with at-stop displays, but the others not. Commuters can only access to information by using their cell phone or waiting for the broadcaster delivering public announcement, which is every 5 to 10 minutes.

Another limitation is the limited focus group in this research. Due to the limited time frame of master's thesis, this thesis decided to focus on commuting trips and also on the rapid rail systems only. The model cannot be applied to do full population analysis. Also, the SC experiment was designed with a given setting, which is morning peak from home to work, school, or university. This model could catch the behavior of trip departing from home but may be biased in predicting returning trip back home.

Another limitation is the model estimation. In this thesis, a multinomial model is estimated. For that, the IIA property is assumed to be true. However, this might not be true. Some similar option might be overestimated, such as "Stay & wait" & "Use another PT line". As to "Use my car" and "Use carsharing", they are quite similar, but driver need to meet different requirements to use them.

The last limitation is in the case study. Since no shuttle service on the unaffected section is included in the case study, the percentage of affected passenger might be overestimated. Take the scenario in the case study as an example, MVG usually provide service between Feldmoching-Hauptbahnhof and Kolumbusplatz-Messestadt Ost. In the real case, only the passengers enter or alight in the disrupted section and passing through the affected section are affected.

8.4 Recommendation and further works

There are few recommendations of further works in the

1. Considering other transit modes and trip purposes

   This thesis decided to focus on rapid rail commuters due to the limited time frame. However, rail commuters only account for around 50% of the users. There are still many other PT users in the systems, especially the PT intermodality in the study area is very high. Service, fare, and information of different PT systems are integrated. It would be meaningful to expand the target group and have a more extensive study on the replanning behavior.

2. Considering the stage of trip in scenario

   The length of service disruption is the main investigating object in this thesis, so the stage of the trip is not considered this time. The on board affected and en-route affected passengers are considered the same. According to Lin et al. (2016) stage of trip might also influence the replanning decision, that's why it is recommended to add this variable for studying the behavior. However, if further research decides to go into spatial details, it is recommended to have a more customized experimental design; for example, using the simulator to generate the route used by the respondents. Respondents can feel more realistic and make reliable choice.

3. Considering the two phases of replanning

   According to Rahimi et al. (2019) the decision making process of replanning is in two phases. First, commuters would wait for a while before thinking of replanning. The second phase for replanning happens when they reach their tolerance of waiting and don't want to wait anymore. Even though this research included three scenarios of disruption duration to catch the tolerance in waiting, the assumption is that delay time is perfect information to commuters. This assumption is true in the U-Bahn system but not always true in the S-Bahn network. Hence, the research in tolerance of waiting could be helpful to supplements the results in S-Bahn commuters.

4. Incorporating RP and SP survey

   This thesis totally relies on SP survey. Even though the author tried to pitch this research and motivate commuters to take party in this survey, some responses are not reliable. The author applied some validation to sort out invalid responses, but the validation rule cannot sort out those who reply wrongly with purpose. If it is possible, considering integrating RP with SP might increase the data reliability and analysis effectiveness.

5. Validating MATSim assignment with PT network and doing more scenario

   This thesis does not validate the MATSim assignment model because this is not the core part of the thesis. If this model is going to be applied in policy implication, validation work shall be done first. Otherwise, there is a high risk that the model cannot reflect reasonable behavior of the commuters.

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Declaration concerning the Master's Thesis

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

Munich, February 07th, 2020

Wei-Chieh Huang

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Appendix A: Interview Minutes

Date: September 24th, 2019

Place: Stadtwerke München (SWM)

Interviewee: Mr. Mathias Gerlach (Fachteamleitung Fahrgastinformation der SWM)

Discussions:

1. **What is the definition of a service disruption in MVG's daily operation?**

- In MVG, there is no specified definition of service disruptions, but a general deliberation is any event that interrupts scheduled services.
- Service disruptions can be classified into minor and major disruptions, which are distinguished by control center conductors' experience and the number of affected passengers.
    1. Minor events: lower number of affected passengers, shorter disruption time around 10~15 minutes, and available complementary alternatives nearby
    2. Major events: larger number of affected passengers and the disruption time for more than an hour

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2. **What are the causes of service disruptions in MVG's daily operation?**

- Several events lead to service disruptions in public transit systems, which can be distinguished into unexpected and expected events:
    1. Unexpected events:
        - Technical problems: vehicles and infrastructures mal functions
        - Massive failures of certain vehicle model: no enough replacement vehicles available and long bureaucratical purchasing process for supplements (The situation for tram is especially hard because of the complex vehicle type composition in tram system.)
        - Weather: critical condition, such as the first snowing day every year (The situation is more severe for bus and tram because they are interacted with surface traffic.)
        - Diseases: shortage of available drivers during the flu season
        - Accidents: personal accidents, such as suicide, in the U-Bahn and vehicular accidents in bus and tramway systems
        - High traffic density during peak hours: interference from the long alighting and boarding in transit system and the interference from other road traffic (This issue is more critical to bus and tramway.)
    2. Planned events:
        - Special activities: higher passenger volume during Oktoberfest, Messe or football matches
        - Strikes: shortage of available personals
        - Construction: shortage of available road or signal infrastructures (Usually the three hours' time window from 1 to 4 o'clock is not sufficient for effective construction work, extension on blocking time is needed.)

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3. What are the consequences of service disruptions?

- Service disruptions induce impacts on both passengers' and operators' sides:
  1. On passengers' side: delay, service cancellation, the crowdedness of the next coming trains, irregular service interval, misconnection of various transport means and modes, and the reduced reliability of the public transit systems
  2. On operators' side: additional efforts in coordinating vehicles and drivers because of the legal working hour constraints and additional effort in service repairing, including repairing vehicles and infrastructures

4. What are the common temporal and spatial impacts of service disruptions in MVG's daily operation?

- The events triggering service disruptions is usually a local point issue. The location of the disruptions and the disruption event itself play a decisive role. If the event leads to one track closure, the service can be maintained with limited service runs. If both tracks are closed, the impacts are more severe and train vehicles need to be rerouted; for example, redirecting vehicle from U5 to U2.
- The consequences of service disruptions are also time dependent. The service disruption is more severe in peak-hours, such as from 8 to 10 o'clock, and peak-seasons, such as winter.

5. What is the frequency of service disruption in MVG's daily operation?

- In general, 89% of MVG's services are delivered on time. However, there is no accurate statistics on MVG's service disruptions because the control center receives roughly 45,000 radio calls regarding any disruptions in 2018. The radio calls contain not only service disruptions but also facility issues such as an elevator at a station is not functioning. Severe service disruptions are rare and happened around 1 to 2 times per month in 2018.

6. Is there a trend of service disruptions across seasons?

- Summer: less riders (no school, use another transport modes) and less stress on services
- Winter: weather issues on the infrastructure

7. How does MVG's control center receive disruptions' information?

- Control center receives disruptions' information from the following three sources:
  1. CCTV monitor enable the control center coordinators to obtain information about the disruption event and its seriousness.
  2. Local colleagues in stations provide on-site information and first solutions.
  3. Cruising colleagues are widely spread in the city (5 vehicles 7/24 hours) for identifying problems and providing first solutions.

8. How does MVG determine the delay time or estimate the arrival time of next service?

- The delay time is determined by collogues' experience.
- As to the estimated arrival time of next train services, the accuracy is not high enough so far. The vehicle and service re-scheduling software was developed in 1990s and was not fully automatic. The schedule and the service frequency are required parameters for the software, so the software cannot adapt any changes based on current condition. Most of the time, no local feasible solution can be found. New software is planned to be installed soon and is expected to provide better prediction on the estimated arrival time of next train in the future.

9. How and how quick can the information be processed to passengers?

- Two information transmitting methods are used: One is text-based and the other is audio-based announcement. The time for transmitting first information to passengers is within a few minutes but not always achievable in the reality due to the limited number of staffs. In current situation, the information transmitting time is not slow, but it can be faster in the future. Text- and template-based passenger information system will be installed in 2020 and the new system could further reduce the reaction time.
- Several channels, such as displays at stations, trains and announcement, websites, and apps in cellphones are used to provide passengers guidance.

10. How does MVG decide which measures to be implemented in order to mitigate the impacts of service disruptions?

- There is no standardized playbook about the mitigation methods and it's all about experience and teamwork. The first important goal to be achieved is clearing the disruption. Bringing the system back to normal status comes at the second.
- Even though the system is interrupted, the priority is to maintain regular service by avoiding problematic sections.
    1. Bus can be replaced by stand-by bus and their routes can be diverted easily.
    2. Tram can also be rerouted or diverted easily. Stand-by tram is less feasible but cooperating with other modes is possible. For example, taxi was implemented for the disruption on Tram 20 between Westfriedhof and Moosach (3 stations). 15~20 taxis were scheduled to provide shuttle services, but the shuttle services were not so acceptable for riders because of the worry of getting charged.
    3. U-Bahn: replacement for U-Bahn is impossible because at least 10 buses are needed to replace a U-Bahn service. Replacement was once done between Harthof and Feldmoching where the demand is not dense and not so large scale. As to rerouting, U-Bahn has less flexibility because the location of depots and turn-outs might be too far away or insufficient.
- There are some case specific measures; for example, dedicated bus lanes can prevent disruption events caused by high car traffic volume.
- In case of strikes, the workers union usually inform the operators at least 24 hours ahead. The goal of MVG is to inform the passengers as earlier as possible to encourage commuters to do rerouting, carpooling, biking, or changing departure time. It is unfortunately impossible to make any cooperation with other operators to fill up the service gaps because of the short reaction time. Working schedule and ta for drivers are usually announced one week ahead. The operators would prefer to maintain regular service on some lines with limited labor forces and coordinated the existing services.

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Appendix B: Statistics of Service Disruption

Table 32 Service Disruption Records

Date	System	Affected Lines	Disruption Event	Temporal Impacts	Spatial Impacts	Severity
2019.11.19	Bus	197	Verkehrsunfall	Verspätungen	Ausfällen	minor
2019.11.19	Bus	zahlreichen MVG Buslinien	Verkehrsbedingte Behinderungen	Verspätungen	vereinzelten Fahrzeugausfällen und vorzeitigen Wendungen	minor
2019.11.19	S-Bahn	All S-Bahn	Verkehrsbedingte Behinderungen	Unklar	Teilausfällen	minor
2019.11.19	Tram	15	Technische Störung an einem Fahrzeug	Verspätungen	Ausfällen	major
2019.11.19	U-Bahn	U3	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 16 Zugausfällen	minor
2019.11.19	U-Bahn	U6	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 19 Zugausfällen	minor
2019.11.22	S-Bahn	All S-Bahn	Ärztliche Versorgung	Verzögerungen von 10 bis 15 Minuten	kurzfristig zu vorzeitigen Zugwenden kommen	minor
2019.11.25	S-Bahn	S7	Technische Störung an einer Weiche	Verzögerungen von bis zu 10 Minuten	kurzfristig zu vorzeitigen Zugwenden kommen und Pendelverkehr	minor
2019.11.26	S-Bahn	All S-Bahn	Ärztliche Versorgung	Verzögerungen von 10 bis 15 Minuten	kurzfristig zu vorzeitigen Zugwenden kommen	minor
2019.11.28	S-Bahn	All S-Bahn	Ärztliche Versorgung	Verzögerungen von 10 bis 15 Minuten	kurzfristig zu vorzeitigen Zugwenden kommen	minor
2019.12.01	S-Bahn	S8	Betriebliche Gründen	Unklar	entfallen 4 Zuge	minor

Date	System	Affected Lines	Disruption Event	Temporal Impacts	Spatial Impacts	Severity
2019.12.03	S-Bahn	S2	Betriebliche Gründen	Unklar	entfallen 3 Zuge	minor
2019.12.03	S-Bahn	S8	Betriebliche Gründen	Unklar	entfallen 4 Zuge	minor
2019.12.05	S-Bahn	All S-Bahn	Technische Störung an einem Stellwerk	Unklar	Bahnhof München Ostbahnhof derzeit kein S-Bahnverkehr möglich	major
2019.12.05	S-Bahn	All S-Bahn	Verkehrsbedingte Behinderungen	Unklar	Teilausfällen	minor
2019.12.05	S-Bahn	S2	Betriebliche Gründen	Unklar	entfallen 3 Zuge	minor
2019.12.06	S-Bahn	All S-Bahn	Technische Störung an einem Stellwerk	Fahrplanabweichungen	Zugausfällen	major
2019.12.09	S-Bahn	S3	Technische Störung an einer Weiche	Unklar	Änderung der Linienführung	major
2019.12.09	S-Bahn	S7	Technische Störung an der Oberleitung	Unklar	Zugausfällen	major
2019.12.09	U-Bahn	U4/U5	Technische Störung an einem Fahrzeug	Verspätungen	vereinzelten Zugausfällen	major
2019.12.09	U-Bahn	U7	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 7 Zugausfällen	minor
2019.12.11	Bus	68	Verkehrsunfall	Verspätungen	vereinzelten Fahrzeugausfällen und vorzeitigen Wendungen	minor
2019.12.11	Bus	zahlreichen MVG Buslinien	Verkehrsbedingte Behinderungen	Verspätungen	vereinzelten Fahrzeugausfällen und vorzeitigen Wendungen	minor
2019.12.11	S-Bahn	All S-Bahn	Technische Störung an einem Fahrzeug	Verzögerungen bis 15 Minuten	Teilausfälle	minor
2019.12.12	Bus	62	Feuerwehreinsatz	Verspätungen	Die Haltestellen ausfallen	major

Date	System	Affected Lines	Disruption Event	Temporal Impacts	Spatial Impacts	Severity
2019.12.12	Bus	zahlreichen MVG Buslinien	Verkehrsbedingte Behinderungen	Verspätungen	vereinzelten Fahrzeugausfällen und vorzeitigen Wendungen	minor
2019.12.12	U-Bahn	U7	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	2 von 7 Zugausfällen	minor
2019.12.13	U-Bahn	U2	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 19 Zugausfällen	minor
2019.12.13	U-Bahn	U3/U6	Technische Störung an einem Fahrzeug	Verspätungen	vereinzelten Fahrzeugausfällen	major
2019.12.13	U-Bahn	U5	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 13 Zugausfällen	minor
2019.12.13	U-Bahn	U7	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 7 Zugausfällen	minor
2019.12.16	S-Bahn	All S-Bahn	Technische Störung an einem Fahrzeug	Verzögerungen bis zu 10 Minuten	Teilausfällen und Änderung der Linienführung	minor
2019.12.16	U-Bahn	U3	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	3 von 16 Zugausfällen	minor
2019.12.16	U-Bahn	U4	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 8 Zugausfällen	minor
2019.12.16	U-Bahn	U6	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	2 von 19 Zugausfällen	minor
2019.12.17	Bus	53/62/63	Feuerwehreinsatz	bis 10:00 Uhr andauern	Die Haltestellen ausfallen	major
2019.12.17	Bus	zahlreichen MVG Buslinien	Verkehrsbedingte Behinderungen	Verspätungen	vereinzelten Fahrzeugausfällen und vorzeitigen Wendungen	minor
2019.12.17	S-Bahn	S1	Betriebsstörung	Unklar	Änderung der Linienführung	major

Date	System	Affected Lines	Disruption Event	Temporal Impacts	Spatial Impacts	Severity
2019.12.17	S-Bahn	S2	Technische Störung an einem Bahnübergang	Verzögerungen bis zu 10 Minuten	Unklar	minor
2019.12.17	S-Bahn	S8	Technische Störung an einem Signal	Verzögerungen bis zu 10 Minuten	Teilausfälle	minor
2019.12.17	Tram	15	Technische Störung an einem Fahrzeug	Verspätungen	Ausfällen	major
2019.12.17	U-Bahn	U2	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	2 von 19 Zugausfällen	minor
2019.12.17	U-Bahn	U3	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 16 Zugausfällen	minor
2019.12.17	U-Bahn	U4	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 8 Zugausfällen	minor
2019.12.17	U-Bahn	U5	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 13 Zugausfällen	minor
2019.12.17	U-Bahn	U6	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 19 Zugausfällen	minor
2019.12.18	S-Bahn	All S-Bahn	Technische Störung an einem Signal	Fahrplanabweichungen	Zugausfällen	major
2019.12.18	U-Bahn	U3	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	3 von 16 Zugausfällen	minor
2019.12.18	U-Bahn	U6	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	2 von 19 Zugausfällen	minor
2019.12.18	U-Bahn	U7	Betriebliche Gründen	Taktlücken und längeren Wartezeiten	1 von 7 Zugausfällen	minor

Note: the numbers represent the number of disruption events instead of the number of affected lines. The classification of major and minor was done by author and the major disruptions include delay time longer than 15 minutes, change of line services, and large service cancellation.

Source:

Appendix C: Collected Variables of the SP Survey

The collected variables of the SP survey are listed in Table 33.

Table 33 Collected variables of the SP survey

Question code	Content	Label
W01	Occupation	Full-time employed Part-time employed Apprenticeship Student: school Student: university or college Other
W02	Home-office possibility	Yes No I don't know No answer
W03	Departure time	HH:MM
W04	Arrival time	HH:MM
W05	Core working/studying hour	Yes No
W06	Latest arrival time	HH:MM
W07	Working/studying hour per day	2 hours 3 hours 4 hours 5 hours 6 hours 7 hours 8 hours More than 8 hours Other
T01	Ticket	IsarCard 9Uhr IsarCard Monthly (incl. year ticket) IsarCard Semester IsarCard Weekly School student tariff monthly School student tariff weekly Solidary Fee (University student ID) Single day ticket Single ticket Stripe ticket Other
T02	Journey Time	(in min)

Question code	Content	Label
T03	Frequency of traveler information acquisition	Always (100%) Usually (75%) Often (50%) Sometimes (25%) Never (0%)
T04	Access mode to the 1st rail stop/station	Walk Scooter Scooter sharing Bike Bike sharing Motorcycle Motorcycle sharing Bus Car Carsharing Kiss & Ride Tram
T05	Access time	(in min)
T06	The 1st railway line	(name of the line)
T07	The last railway line	(name of the line)
T08	The 1st rail station/stop	(name of the station/stop)
T09	The last rail station/stop	(name of the station/stop)
S01	Subscription of sharing mobility	No Scooter sharing Bike sharing Motorcycle sharing Carsharing
D1	Age	Under 18 years old 18 - 19 years old 20 - 24 years old 25 - 29 years old 30 - 34 years old 35 - 39 years old 40 - 44 years old 45 - 49 years old 50 - 54 years old 55 - 59 years old 60 - 64 years old 65 - 69 years old 70 - 74 years old 75+ years old

Question code	Content	Label
D2	Gender	male female diverse
D3	Country/continent of origin	Germany Europe (except for Germany) Asia Africa North America South America
D4	Completed education	Primary school degree Secondary school degree Bachelor's degree Master's degree or diploma Doctorate Other
D5	Living year in Munich	Less than 3 months 3 ~ 6 months 6 ~ 12 months 1 ~ 2 years More than 2 years
D6	Individual transportation mode availability	Scooter Bike Moped Motorcycle Car None of above
D7	Driving license availability	Class A Class B Class C Class D No
D8	Income	Less than 500 € 500 to less than 1000 € 1000 to less than 2000 € 2000 to less than 3000 € 3000 to less than 4000 € 4000 to less than 5000 € 5000 to less than 6000 € 6000 to less than 7000 € More than 7000 € Prefer not to answer

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Appendix D: Calculation of Delay Time

The main source for delay time calculation is the Mobilität in Deutschland (MiD2017) (Bundesministerium für Verkehr und digitale Infrastruktur, 2017). The "Wege Lokale" and "Ettape Lokale" datasets were used to derive important parameters, such as access distance, trip distance, speed of car, and speed of PT. In addition, some other data sources and assumptions were made to fill the gaps of MiD2017 data. Last but not least, parameters for validating the total travel time were also obtained from the MiD2017 dataset as well. The followings provide more detail.

1. Access time

   Access time in this research is not exactly the same as the travel time from home to PT stations. It is the travel time from the PT station to the next alternative, such as next PT station or PT commuters' home. The access time for using another PT line is calculated by average distance between PT stations divided by PT speed. The access time for using own car is calculated by access distance from home to rail station divided by the PT speed. Due to the lacking information about the access time to carsharing, an assumption of 5 minutes was made. As to the other options, they have no access time.

2. Waiting time

   Waiting time is the time that people waiting for the next service, which is usually happen to PT or taxi. The waiting time of "Stay & wait" is the disruption time of the three scenarios, which are 10, 20, and 30 minutes. The waiting time of "Use another PT line" is 8 minutes. The waiting time of taxi is assumed as 5 minutes.

3. In-vehicle time (IVT)

   In-vehicle time is the time that commuters spent in the vehicle. The calculation of the IVT is the trip distance (18 km) divided by the speed of PT or car. In addition, for car users, additional parking searching time should be added. The calculated IVT for "Stay & wait", "Use another PT line", "Use carsharing", and "Take taxi" are 31, 31, 29, 29, 22 minutes respectively.

After all the total travel time components of each option were derived, the values were validated by checking with the MiD2017 data. The total travel time of each option is checked with the travel time of each corresponding mode in the survey data.

Table 34 Calculation of delay time

Alternatives	Access time	Waiting time	In-vehicle time
Stay & wait	-	Disruption time = 10, 20, or 60 minutes by scenarios	Average trip distance (18 km)/ PT speed (35 km/h) = 31 min.
Use another PT line	Average distance between PT stations (0.2 km) / Walk speed (5 km/h) = 2 min.	Average of S-Bahn's average waiting time (10 min.) and U-Bahn's average waiting time (5 min.) = 8 min.	Average trip distance (18 km)/ PT speed (35 km/h) = 31min.
Use my own car	Access distance from home to rail station (2.8 km)/ PT speed (35 km/h) = 5 min.	-	Average trip distance (18 km)/ PT speed (50 km/h) + Parking searching time (8 min.) = 29 min.
Use carsharing	Assumption = 5 min.	-	Average trip distance (18 km)/ PT speed (50 km/h) + Parking searching time (8 min.) = 29 min.
Take taxi	-	Assumption = 5 min.	Average trip distance (18 km)/ PT speed (50 km/h) = 22 min.
Cancel the trip	-	-	-
Other	-	-	-

*Parking searching time: https://www.parking-net.com/parking-news/inrix/germans-41-hours-searching-parking

Appendix E: Calculation of Additional Cost

The calculation of additional travel cost of each replanning option is summarized in Table 35. They are explained respectively in the followings.

1. Using another PT

   We assumed commuters bought a ticket already and then found out the service disruption, so they could obtain "Anschlussticket" for one or two rings, which cost 1.2 and 2.1 euros respectively. However, some people might have a transit pass covering larger zones, so no additional travel cost is also possible.

2. Use my own car

   The cost for using the car in this case is the operational cost consisting of fuel cost for the trip and parking fee.

3. Use carsharing

   The cost for using carsharing is driving time according to the calculation of DriveNow.

4. Take taxi

   The cost for taking taxi have two components: one is the starting price and the other is the distance-based cost. The calculation is based on municipality's rule.

Table 35 Calculation of additional travel cost

Alternatives	Additional cost
Stay & wait	-
Use another PT line	0, 1.2, 2.1 euros
Use my own car	Average trip length (18 km) * Oil price (1.5 euro/l) * Fuel efficiency (0.04 l/km) + Parking price (6 euros/day) =7.1 euros
Use carsharing	IVT (29 min) * Rental fee (0.3 euro/min) = 8.2 euro
Take taxi	Starting price (3.7) + Average trip length (18 km) * Kilometer price (1.7 euro/km) = 34.8 euros
Cancel the trip	-
Other	-

*Carsharing price: https://www.drive-now.com/de/en/how-it-works/

*Taxi price: https://www.muenchen.de/int/en/traffic/taxi/fares.html

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Appendix F: SP Survey

Welcome page

Language: English Change the language

Modeling Rapid Rail Commuter's Trip Re-Planning Behavior

How would you re-plan your trip when the rapid railway service was interrupted?

Dear participants,

Thank you for your interest in this research and welcome to this survey.

My name is Wei-Chieh Huang and I am doing this survey for my master's thesis supervised by the Professorship of Modeling Spatial Mobility of Technical University of Munich.

This survey is to explore how rail commuters re-plan their trips in response to unexpected disruptions of regional train, S-Bahn and U-Bahn service. This research aims to develop a better mobility concept in Munich! So your participation in this survey is very important!

If you:

1. commute by **regional train**, **S-Bahn** or **U-Bahn** within the **MVV** network and
2. study or work in **Munich Metropolitan Area**,

you are kindly invited to complete this 10 minutes survey. Participation in this research is voluntary and all data will be handled anonymously.

If you understand the above information and agree to participate in this study, please click "Next" to continue. In case of any concern, please do not hesitate to contact me via email: weichieh.huang@tum.de

Thank you very much for your support!

Student: Wei-Chieh Huang

Supervisors: Mr. Nico Kühnel, Prof. Dr.-Ing. Rolf Moeckel

Technische Universität München

Filtering question

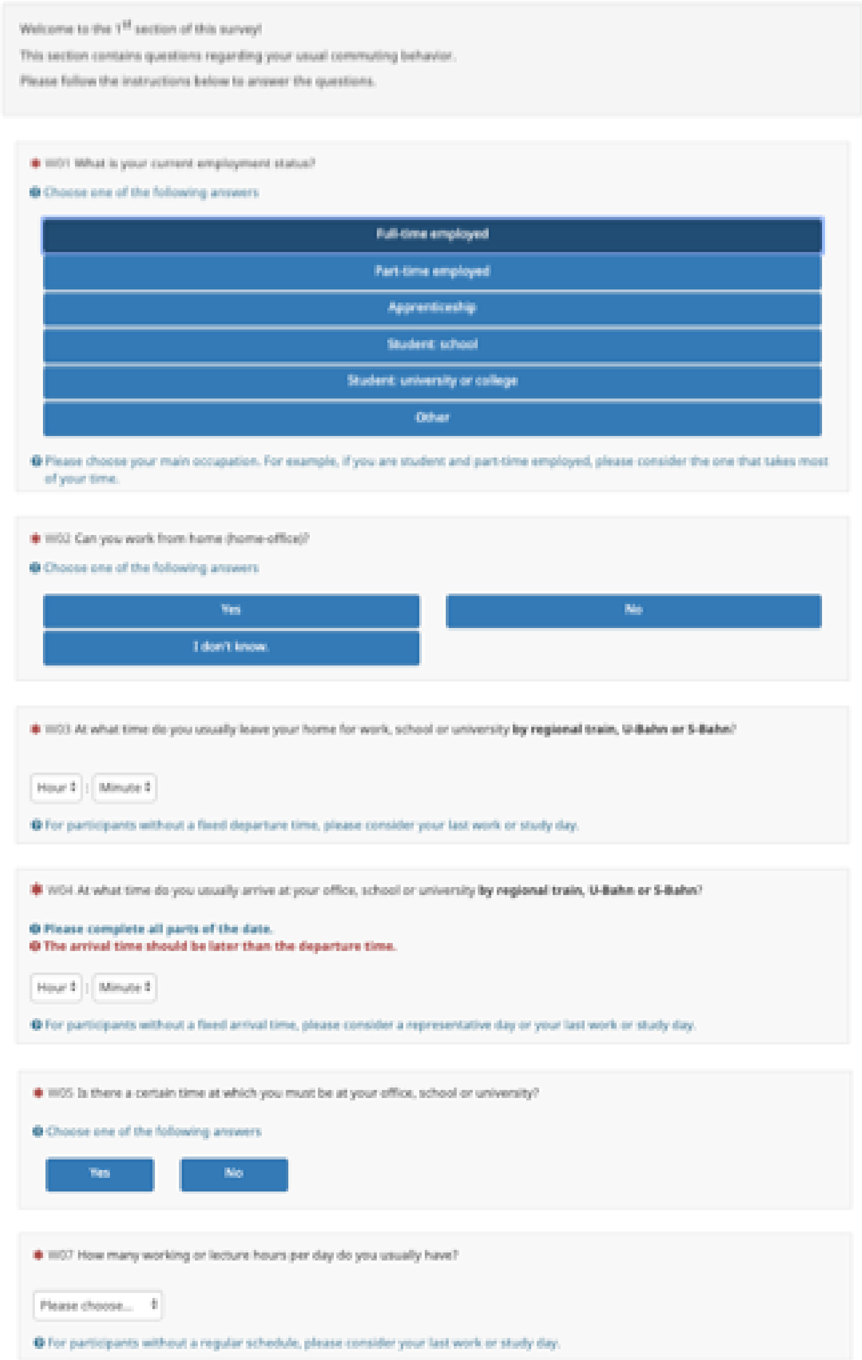
* O1 Do you commute to work, school or university **by regional train, S-Bahn or U-Bahn in the MVV Network** **at least one day in a month**?

Choose one of the following answers

Yes No

O2 Please click on "Next" to continue the survey.

Part 1.
Daily working/studying routine



Welcome to the 1st section of this survey!

This section contains questions regarding your usual commuting behavior.

Please follow the instructions below to answer the questions.

WO1 What is your current employment status?

Choose one of the following answers

Full-time employed

Part-time employed

Apprenticeship

Student: school

Student: university or college

Other

Please choose your main occupation. For example, if you are student and part-time employed, please consider the one that takes most of your time.

WO2 Can you work from home (home-office)?

Choose one of the following answers

Yes | No

I don't know.

WO3 At what time do you usually leave your home for work, school or university **by regional train, U-Bahn or S-Bahn**?

Hour : Minute

For participants without a fixed departure time, please consider your last work or study day.

WO4 At what time do you usually arrive at your office, school or university **by regional train, U-Bahn or S-Bahn**?

Please complete all parts of the date.

The arrival time should be later than the departure time.

Hour : Minute

For participants without a fixed arrival time, please consider a representative day or your last work or study day.

WO5 Is there a certain time at which you must be at your office, school or university?

Choose one of the following answers

Yes | No

WO7 How many working or lecture hours per day do you usually have?

Please choose...

For participants without a regular schedule, please consider your last work or study day.

Part 2.
Daily Commuting
Trip

Part 2.
Daily Commuting
Trip (cont.)

* T04 Which mode(s) do you usually use to go to the 1st regional train, S-Bahn or U-Bahn stop/station from home?
(If you walk from your home to a bus stop and then take the bus to the 1st regional train, S-Bahn or U-Bahn stop/station, please select both walk and bus.)

Check all that apply

- ☐ Walk
- ☐ Scooter or E-scooter
- ☐ E-scooter-sharing
- ☐ Bike or E-bike
- ☐ Bike-sharing
- ☐ Motorcycle or E-motorcycle
- ☐ E-motorcycle-sharing
- ☐ Bus
- ☐ Car
- ☐ Carsharing
- ☐ Kiss & Ride
- ☐ Tram
- ☐ Other:

For participants without a regular schedule, please consider your last work or study day.

* T05 How much time does it usually take you from home to the 1st regional train, S-Bahn or U-Bahn stop/station?

Only numbers may be entered in this field.
Your answer must be at least 0.1

approximately ______ minutes

For participants without a regular schedule, please consider your last work or study day.

* B00 **Which regional train, S-Bahn or U-Bahn line** do you usually use **at the beginning of your commuting trip**?
(Bus or tram trip to the 1st regional train, S-Bahn or U-Bahn stop/station is not counted, please only input the 1st regional train, S-Bahn or U-Bahn line in your commuting trip.)

Choose one of the following answers

S3

For participants without a regular schedule, please consider your last work or study day.
If the railway line is not listed below, please select "Other" and manually key in the railway line that you use.

* B03 At which stop/station of the S3 do you usually start your commuting trip?

Choose one of the following answers

Please choose...

For participants without a regular schedule, please consider your last work or study day.
If the railway stop/station is not listed below, please select "Other" and input the railway stop/station that you use.

* E00 **Which regional train, S-Bahn or U-Bahn line** do you usually use **before the end of your commuting trip**? If you use only one regional train, S-Bahn or U-Bahn line, please select the same line again.
(Bus or tram trip from the last regional train, S-Bahn or U-Bahn stop/station to your office or school is not counted, please only input the last regional train, S-Bahn or U-Bahn line in your commuting trip.)

Choose one of the following answers

S3

For participants without a regular schedule, please consider your last work or study day.
If the railway line is not listed below, please select "Other" and manually key in the railway line that you use.

* E03 At which stop/station of the S3 do you usually end your commuting trip?

Choose one of the following answers

Please choose...

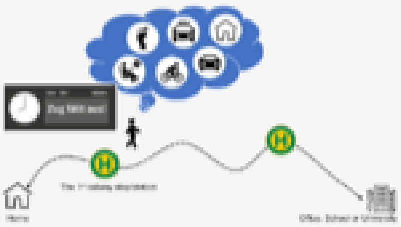
For participants without a regular schedule, please consider your last work or study day.
If the railway stop/station is not listed below, please select "Other" and input the railway stop/station that you use.

Part. 3
Choice experiment
(validation question)

Welcome to the core part of this research!

This time you will be presented with 9 choice games with different scenarios. The scenarios are built with different delay times and various re-planning possibilities. We would like to know how you react to different delay time and cost of each re-planning possibilities. The re-planning possibilities include "Stay & wait", "Use another public transport line", "Use my own car", "Use carsharing", "Take taxi", "Cancel the trip" or something else.

(Maybe there is no alternative public transport line available for you between your home and office, but please imagine that there is one.)



Please answer the two questions below and then the experiment will start.

* S01 Do you subscribe to any shared mobility services?

Check all that apply
Please verify your answer.

- [ ] No subscription
- [ ] E-Scooter-Sharing
- [ ] Bike-Sharing (or E-Bike-Sharing)
- [ ] E-Motorcycle-Sharing
- [ ] Carsharing
- [ ] Other:

* S02 Do you have your own car or your household members' cars to drive to office, school or university?

Choose one of the following answers

Yes

Not always

No

3-1. Choice Experiment: Scenario 1 ~ 3

Part. 3
Choice experiment
(introduction)

Welcome to the first 3 Scenarios!

Please imagine that your are waiting for the S3 line at the Gernlinden station as usual on a comfortable winter day whithout rain or snow.

The train should come in a few minutes and you plan to arrive at your destination at 09 : 20 as your regular plan. Also, you need to be there at 10 : 40.

Suddenly, the on-platform display shows:

SC100 The next three pages will show you the scenarios with **10 minutes delay**.

Each page will show you a table with a set of re-planning options and their features. The features that you need to consider are:

1. **Additional cost**: the amount of money that needs to be paid additionally to choose this option, even though you have a ticket already
2. **Estimated arrival time**: your regular arrival time plus or minus delay time of this option
3. **Requirement**: condition for choosing this option; for example, car availibility and driving license

Note that the features in each page are different, so please pay attention to each table.

All the scenarios and tables are hypothetical and not necessarily realistic. There is no right or wrong answer. We are simply interested in your opinion. Please click on "Next" to continue the survey.

Part. 3
Choice experiment
(1/9)

3-104. Choice Experiment

* SC104 You are waiting for the S3 line at the Gernlinden station and you plan to arrive at your destination at 09 : 20. Also, you need to be there at 10 : 40.

Please consider the following re-planning options and their features, such as additional cost, estimated arrival time and requirement.

Re-planning options	Additional cost	Estimated arrival time	Requirement
Stay & wait	-	09 : 20 +10 min.	-
Use another public transport line	+2.1 €	09 : 20 +2 min.	-
Use my own car	+10.0 €	09 : 20 +15~20 min.	Car & driving license is needed
Use carsharing	+6.0 €	09 : 20 -10~-15 min.	Carsharing subscription is needed
Take taxi	+25.0 €	09 : 20 -15~-20 min.	-
Cancel the trip	-	-	-
Others	-	-	-

Please choose what you would do.

If none of the options is attractive to you, please select "others" and specify what would you do, such as walk, bike, e-scooter, share car ride with family and so on. Walk and bike has been provided as default for you.

- Choose one of the following answers
- If you choose 'Other:' please also specify your choice in the accompanying text field.
- Please do not select "Use my own car" or "Use carsharing" if you indicate that car is not available to you or you have no subscription on carsharing.

Stay & wait

Use another public transport line

Use my own car

Use carsharing

Take taxi

Cancel the trip

Other: walk

Other: bike

Other

(Maybe there is no alternative public transport line available for you between your home and office, but please imagine that there is one.)

Part. 3
Choice experiment
(2/9)

3-106. Choice Experiment

* SC106 You are waiting for the S3 line at the Gernlinden station and you plan to arrive at your destination at 09 : 20. Also, you need to be there at 10 : 40.

Please consider the following re-planning options and their features, such as additional cost, estimated arrival time and requirement.

Re-planning options	Additional cost	Estimated arrival time	Requirement
Stay & wait	-	09 : 20 +10 min.	-
Use another public transport line	+0.0 €	09 : 20 +18 min.	-
Use my own car	+5.0 €	09 : 20 +15~20 min.	Car & driving license is needed
Use carsharing	+6.0 €	09 : 20 -10~-15 min.	Carsharing subscription is needed
Take taxi	+46.0 €	09 : 20 +5~10 min.	-
Cancel the trip	-	-	-
Others	-	-	-

Please choose what you would do.
If none of the options is attractive to you, please select "others" and specify what would you do, such as walk, bike, e-scooter, share car ride with family and so on. Walk and bike has been provided as default for you.

- Choose one of the following answers
- If you choose 'Other:' please also specify your choice in the accompanying text field.
- Please do not select "Use my own car" or "Use carsharing" if you indicate that car is not available to you or you have no subscription on carsharing.

Stay & wait

Use another public transport line

Use my own car

Use carsharing

Take taxi

Cancel the trip

Other: walk

Other: bike

Other

(Maybe there is no alternative public transport line available for you between your home and office, but please imagine that there is one.)

Part. 3

Choice experiment

(3/9)

3-105. Choice Experiment

* SC105 You are waiting for the S3 line at the Gernlinden station and you plan to arrive at your destination at 09 : 20. Also, you need to be there at 10 : 40.

Please consider the following re-planning options and their features, such as additional cost, estimated arrival time and requirement.

Re-planning options	Additional cost	Estimated arrival time	Requirement
Stay & wait	-	09 : 20 +10 min.	-
Use another public transport line	+2.1 €	09 : 20 +18 min.	-
Use my own car	+10.0 €	09 : 20 +15~20 min.	Car & driving license is needed
Use carsharing	+11.0 €	09 : 20 +15~20 min.	Carsharing subscription is needed
Take taxi	+46.0 €	09 : 20 -15~-20 min.	-
Cancel the trip	-	-	-
Others	-	-	-

Please choose what you would do.

If none of the options is attractive to you, please select "others" and specify what would you do, such as walk, bike, e-scooter, share car ride with family and so on. Walk and bike has been provided as default for you.

- Choose one of the following answers
- If you choose 'Other:' please also specify your choice in the accompanying text field.
- Please do not select "Use my own car" or "Use carsharing" if you indicate that car is not available to you or you have no subscription on carsharing.

- Stay & wait
- Use another public transport line
- Use my own car
- Use carsharing
- Take taxi
- Cancel the trip
- Other: walk
- Other: bike
- Other

(Maybe there is no alternative public transport line available for you between your home and office, but please imagine that there is one.)

Part 4.
Personal attributes

We are almost finished with this survey! Just one section left! Hang in there!

This final section contains questions regarding your personal data because your personal characteristics can influence the trip re-planning behavior. Please answer the following questions truly because these help us to develop a better behavioral model.

The data collected here will not reveal your personal identity and will remain anonymous.

* D1 How old are you?

Choose one of the following answers

- Under 18 years old
- 18 - 19 years old
- 20 - 24 years old
- 25 - 29 years old
- 30 - 34 years old
- 35 - 39 years old
- 40 - 44 years old
- 45 - 49 years old
- 50 - 54 years old
- 55 - 59 years old
- 60 - 64 years old
- 65 - 69 years old
- 70 - 74 years old
- 75+ years old

* D2 What is your gender?

Choose one of the following answers

- male
- female
- diverse

* D3 Where are you from?

Choose one of the following answers

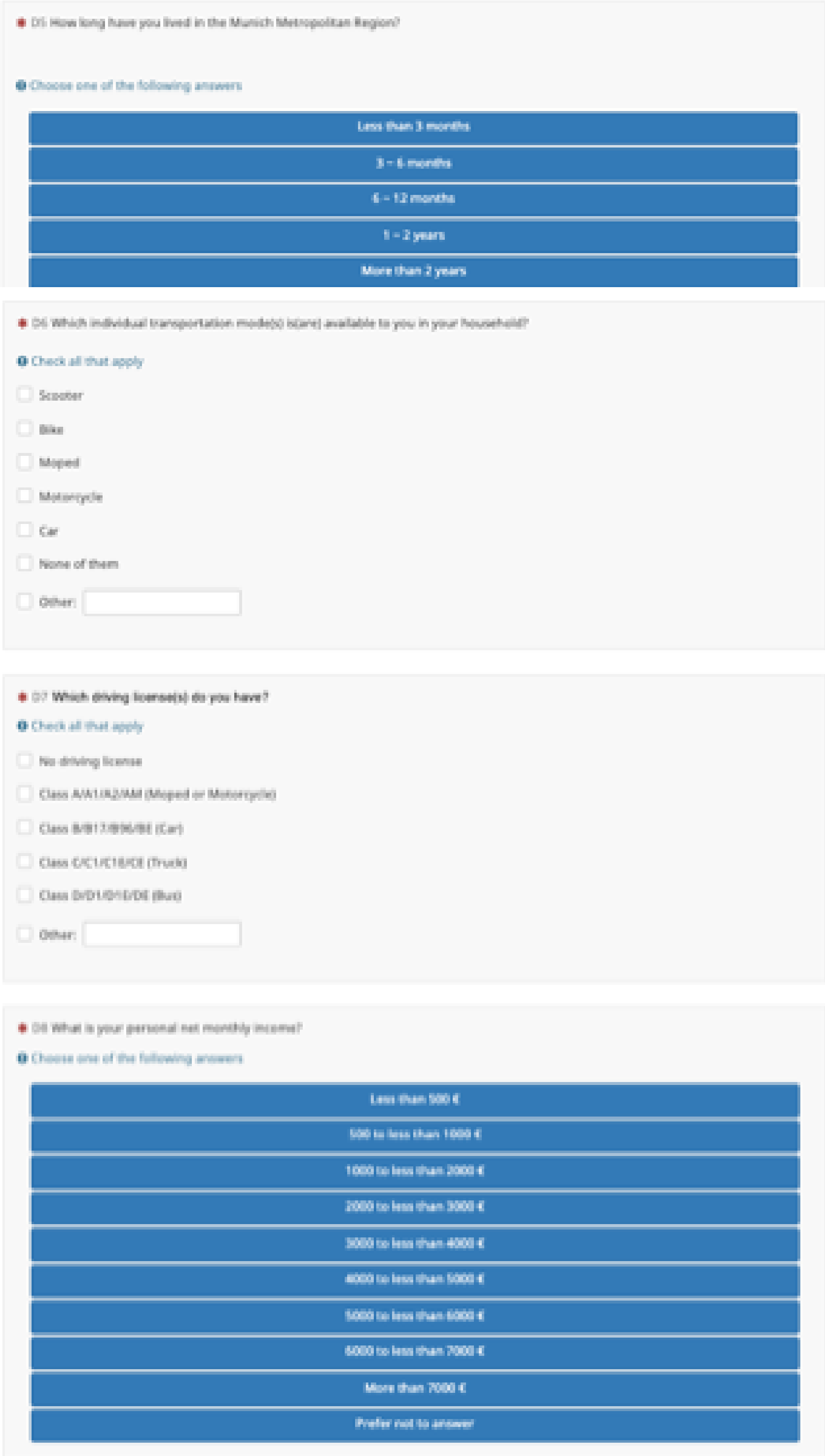
- Germany
- Europe (except for Germany)
- Asia
- Africa
- North America
- South America
- Australia/Oceania
- Other

* D4 What is the highest level of education you have completed?

Choose one of the following answers

- Primary school degree
- Secondary school degree
- Bachelor's degree
- Master's degree or diploma
- Doctorate
- Other

Part 4.
Personal attributes
(cont.)



D5 How long have you lived in the Munich Metropolitan Region?

Choose one of the following answers

- Less than 3 months
- 3 – 6 months
- 6 – 12 months
- 1 – 2 years
- More than 2 years

D6 Which individual transportation mode(s) is(are) available to you in your household?

Check all that apply

- Scooter
- Bike
- Moped
- Motorcycle
- Car
- None of them
- Other:

D7 Which driving license(s) do you have?

Check all that apply

- No driving license
- Class A/A1/A2/AM (Moped or Motorcycle)
- Class B/B17/B96/BE (Car)
- Class C/C1/C1E/CE (Truck)
- Class D/D1/D1E/DE (Bus)
- Other:

D8 What is your personal net monthly income?

Choose one of the following answers

- Less than 500 €
- 500 to less than 1000 €
- 1000 to less than 2000 €
- 2000 to less than 3000 €
- 3000 to less than 4000 €
- 4000 to less than 5000 €
- 5000 to less than 6000 €
- 6000 to less than 7000 €
- More than 7000 €
- Prefer not to answer

Feedback section

Feedback

F1 Would you like to comment on this survey? Please leave us your suggestions and comments here.

Closing page

Thank you for your support! We appreciate your contribution to this survey!

If you have any questions or would like to get informed about the final results of this thesis, please feel free to contact me through email: weichieh.huang@tum.de

If you like the topic of this research and this survey, it would be appreciated if you could forward the link to your family, friends and collegues.

- DE: https://umplanungpt.limequery.com/189413?lang=de
- EN: https://umplanungpt.limequery.com/189413?lang=en

If you are interested in the involved institute, please see more information from: Professorship of Modeling Spatial Mobility, Technical University of Munich: https://www.bgu.tum.de/en/msm/start-page/

You can now safely close the survey. Have a nice day!

Wei-Chieh Huang

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Appendix G: Recruiting Flyer

Figure 35 Survey flyer