KTH ROYAL INSTITUTE
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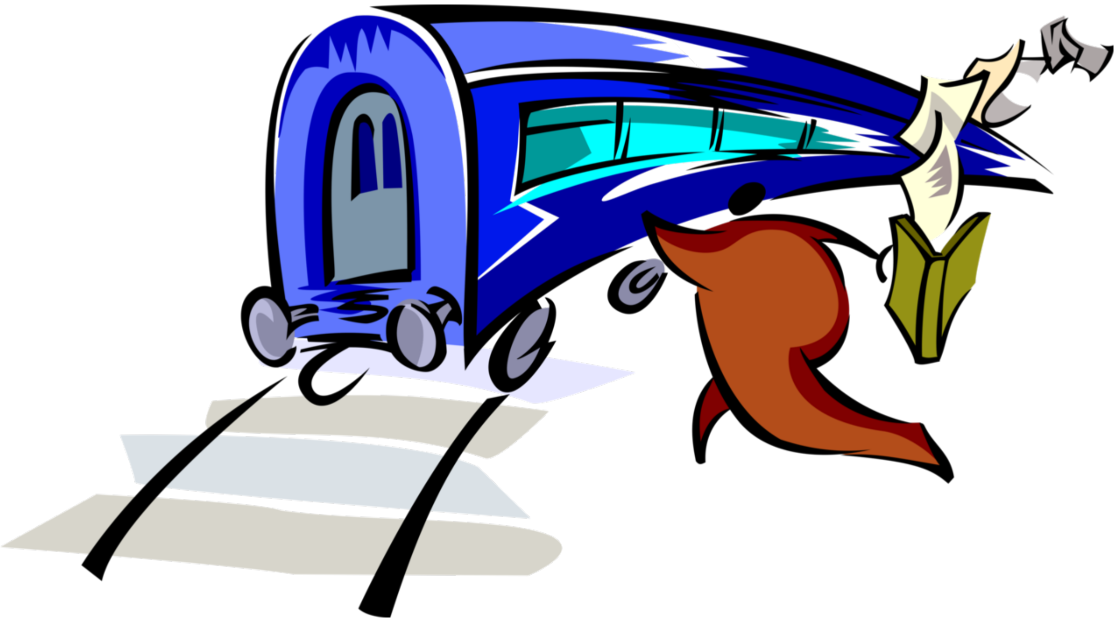
Licentiate thesis in transport science

Improvement of departure time suitability for interregional rail timetables

FÉLIX VAUTARD



Stockholm, Sweden 2020

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Abstract

In order to respond to growing interregional rail traffic, rail capacity should be allocated better. To achieve this, one possibility is to optimise suitability of departure times for rail passengers in the timetabling process. The suitability of departure and arrival times refers to how well the timetable can diminish constraints on passengers that must adapt their activities to train schedules. However, current knowledge on this issue is limited. Indeed, only few studies have quantified how passengers valuate departure time suitability. These studies are also quite brief in their coverage of the influence of travellers' profiles on these valuations. In addition, current methods comparing the socioeconomic consequences of different timetables are not applicable in all contexts, and most of them rely on strong simplifications. In summary, this thesis aims to answer the following research questions:

1. What are the determinants for passenger valuations of departure time suitability?
2. How to improve the welfare assessment of departure time shifts in interregional timetables?

In paper 1, I focus on the first research question. To this end, we present a new study in which we estimate new valuations of departure time suitability. To achieve this, we conducted a stated-preference survey on several Swedish rail lines. We present the design of the survey and its result in the paper. With this work, I aim to fulfil two objectives: first, to provide figures to improve inputs for travel demand forecast models and socioeconomic assessments. Second, to determine the influence of trip characteristics and traveller's socioeconomic profile on their valuations.

In paper 2, I focus on the second research question. To this end, we present a method that enables calculating changes in welfare due to departure time shifts in any interregional timetable. In this method, we bridge schedule-based model forecasts with cost-benefit analysis framework. This enables a better approximation of consumer and producer surplus than in previous literature. In addition, we show the applicability and potential of our method on a case study covering a Swedish interregional line.

Sammanfattning

För att svara mot den växande interregionala järnvägstrafiken bör järnvägskapaciteten fördelas bättre. För att uppnå detta kan man i tidtabellsprocessen optimera lämpligheten för tågpassagerares avgångstid. Lämpligheten för avgångs- och ankomsttider avser tidtabellens förmåga att minska passagerarnas begränsningar när de måste anpassa sin verksamhet efter tågplanen. Men det finns en brist i aktuella kunskaper i denna fråga. Faktum är att endast få studier har kvantifierat hur passagerare värderar lämplighet för avgångstid. Dessa studier är också ganska översiktliga i sin beskrivning av hur resenärers profiler påverkar värderingarna. Dessutom är de nuvarande metoderna som jämför de socioekonomiska konsekvenserna av olika tidtabeller inte tillämpliga i alla sammanhang, och de flesta av dem förlitar sig på starka förenklingar. Sammanfattningsvis har denna avhandling syftat på att svara följande forskningsfrågor:

1. Vilka faktorer påverkar passagerares utvärdering av lämpligheten för avgångs- och ankomsttider?

2. Hur kan man förbättra utvärderingen av skillnader i välfärd av varierande avgångstider för interregionala tåg?

I artikel 1 behandlar vi första forskningsfrågan. För detta ändamål presenterar vi en ny studie där vi analyserar nya värderingar av lämplighet för avgångstid. För att uppnå detta genomförde vi en *stated-preference* undersökning på tre svenska järnvägslinjer. Vi presenterar undersökningens utformning och dess resultat i uppsatsen. Med detta arbete syftar vi till att uppfylla två mål: för det första, att tillhandahålla siffror för att förbättra indata i prognosmodeller för reseefterfrågan och samhällsekonomiska bedömningar. För det andra, att bestämma påverkan av resans egenskaper och resenärers socioekonomiska profil på värderingarna.

I artikel 2 behandlar vi den andra forskningsfrågan. För detta ändamål presenterar vi en metod som gör det möjligt att beräkna förändringen i välfärd på grund av förskjutningar i avgångstiderna i en interregional tidtabell. I den här metoden överbryggar vi kunskapen i schemalagda modeller med kostnads-nyttoanalysramen. Detta möjliggör en bättre uppskattning av konsument- och producentöverskott än i tidigare litteratur. Dessutom visar vi användbarheten av vår metod i en fallstudie som täcker en svensk interregional linje.

Acknowledgments

First, I would like to thank my main supervisor Oskar Fröidh, who hired me in this project and trusted both my decisions and ability to deliver good results all along the way. Thank you also for your great availability. Second, I want to express my deepest gratitude to my co-supervisor Chengxi Liu, who helped me on both the conceptual questions and technical challenges I faced while writing my articles. Thank you also for your great availability and the numerous interesting discussions we had. Moreover, I would like to thank my other co-supervisor Camilla Byström for her help in designing the questionnaire for the first article.

There are many others I would like to thank and without whom the project would not have gone through. Josef Andersson, for your support with the VISUM model and other IT issues, and your major contribution in the case study modelling for my second article. Bo-Lennart Nelldal, for your advice during the model-designing phase; Tom Thöyrä for your reactivity and help with ordering the material for the fieldwork, and obtaining a new computer when my computer died suddenly. My dear colleagues in the Transport division – especially the PhD students – for having enriched my daily life at KTH with many interesting discussions and breaks.

Last, but not least, I would like to thank my girlfriend Juliette and my family for their precious support during these intense years.

List of papers

Vautard, F., Liu, C., Fröidh, O., Byström, C., 2020. Estimation of interregional rail passengers valuations for their desired departure times. Submitt. to Transp. Policy.

Vautard, F., Liu, C., Fröidh, O., 2020. Assessing economic welfare for departure time shifts in interregional rail timetables. Submitt. to Transp. Res. Part A.

Declaration of contribution

For the first paper, Oskar Fröidh and Camilla Byström initiated the idea of conducting a survey on valuations missing in the literature for interregional rail travellers. Then, I did the literature review and proposed focusing the survey on departure time suitability. The questionnaire was achieved through collaborative work. In this task, Oskar Fröidh and Camilla Byström helped greatly in rephrasing the questions to make them more understandable to respondents. On my side, I proposed the drafts for the questionnaire, and I did the design of the choice tasks. I was also in charge of the fieldwork, for which I recruited, supervised and helped staff at rail stations. In addition, I did the survey post-processing and most of analysis of results. Finally, I wrote the entire paper with regular feedback from the co-authors. Chengxi Liu helped greatly in revising the paper.

For the second paper, Oskar Fröidh initiated the idea of using a schedule-based model to tackle the issues with rail capacity allocation. He also started the teamwork with Josef Andersson and Bo-Lennart Nelldal from the KTH transport planning division. Together with Chengxi Liu, we built the schedule-based model used in the case study. Then, Chengxi Liu and I conceptualised the issue with welfare assessment of timetables and developed the method together through many discussions. We also specified the case study to present in the paper together. Next, I did the welfare calculations for the case study. Finally, I wrote most of the paper with frequent feedback from the co-authors.

Contents

1. Introduction

1.1. Background

In most European countries, passenger rail traffic has greatly increased in the last decade. For instance, the Swedish rail traffic increased by 27% between 2008 and 2018 (in person-kilometres) (Trafikanalys, 2019). This increase is good news for society since increasing rail modal share for passenger traffic is a well-known manner to reduce negative externalities (e.g. carbon dioxide emissions) related to car and air travel. However, this increase has saturated rail capacity of certain connections. For instance, a large part of the Swedish rail network is already highly used, as shown in Figure 1 (red lines). This high usage makes available rail capacity much scarcer to supply this growing demand. Consequently, conflicts in rail capacity allocation increase in number, and stakeholders need to find solutions to optimise the capacity allocation processes.

To achieve this, one solution involves understanding passengers' expectations regarding rail supply. This knowledge can then be used to adapt rail supply accordingly. To this end, much research work has aimed at determining economic valuations for different aspects of rail supply. Based on neoclassical economics theory, these valuations allow quantifying and comparing the different aspects of rail supply in order to forecast passenger demand or to make socioeconomic assessments. These valuations are estimated through the regression of discrete-choice models on survey data. These surveys rely on either stated preferences (SP) or revealed preferences (RP). SP data consist of choices made regarding hypothetical situations (e.g. regarding transport mode, or travel time versus price). On the other hand, RP data consist of the records of real choices on the transport system. There are pros and cons in using either method, and a combination of both types of surveys is generally necessary to determine reliable valuations (Louviere et al., 2000). With this methodology, a great amount of research has focused on determining the valuation of travel time savings (Wardman et al., 2016), travel time reliability (Fosgerau and Karlström, 2010; Wardman et al., 2016) and comfort/service levels (Kottenhoff, 1999; Wardman and Whelan, 2011).

Figure 1: Rail capacity usage in Sweden in 2018 during peak times. Extracted from Trafikverket (2018a)[1]

[1] The legend is as follows: Green = low capacity usage; Yellow = medium capacity usage; Red = high capacity usage.

However, the complexity of passengers' preferences is still not fully considered today in timetable planning. Timetable planning (or timetabling) is a part of the rail planning process shown in Figure 2. In timetable planning, the departure and arrival times of each train at each station are determined in order to fulfil the desired line frequencies that have been previously determined during the line planning process (Lusby et al., 2011). Today, rail planners optimise timetables by essentially maximising the usage of rail infrastructure, minimising train delays and travel times, and ensuring passenger transfers (Parbo et al., 2016). Despite these aspects, the current timetabling process does not capture all the expectations of passengers regarding rail supply. For instance, the suitability of departure and arrival times for passengers is not included. Suitability of departure and arrival times refers to the ability of the timetable to diminish constraints on passengers that must adapt their activities to the train schedules. Indeed, interregional trips (trips longer than 100 km) usually have a lower and more irregular frequency than regional or commuter trains. This constrains interregional passengers to adapt their schedule to available departure times, limiting their potential activities for the day. Including such phenomenon in the timetabling process should help improve rail supply and thus contribute to creating a more sustainable transport system.

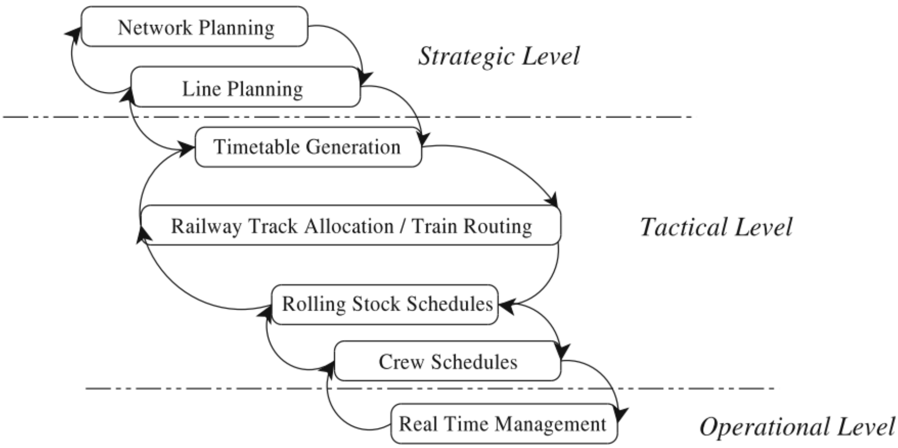

Figure 2: The rail planning process. Extracted from Lusby et al. (2011).

1.2. Valuations of departure time suitability

Departure time suitability is usually approached through the scheduling model introduced by Douglas and Miller (1974), and Small (1982). The scheduling model relies on the concept of *schedule delay (SD)*, defined as the time difference between a passenger's desired departure time and a timetabled departure. For instance, passengers who would like to depart at 10:00 would have a schedule delay of 30 minutes if they take a train departing at 9:30. As explained in our paper Vautard et al. (2020b), we chose to rename the concept of schedule delay as *departure time displacement (DTD)* to avoid the confusion with use of schedule delays to study travel time reliability. With this definition, one can study departure time suitability by determining the valuation of DTD reduction. Since departure and arrival times are dependent on each other, the scheduling suitability issue can be reduced to either departure or arrival times. On this issue, departure times are conventionally chosen in the literature, but the same reasoning can be applied to arrival times. In addition, DTD is usually separated into two components: *Departure Time Displacement Earlier* (DTDE) for earlier departures than desired, and *Departure Time Displacement Later* (DTDL) for later departures than desired, as illustrated in Figure 3.

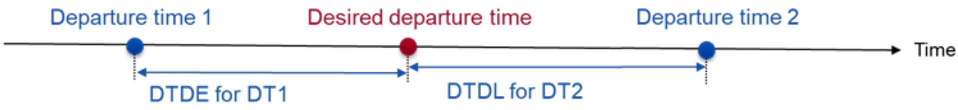

Figure 3: Definition of departure time displacements earlier and later (DTDE and DTDL), extracted from Vautard et al. (2020b).

Although valuations of many aspects of rail supply have been studied, only a small amount of studies have focused on determining valuations for DTD reduction. As evidence, Wardman et al. (2016) counted 14 European studies on this issue, which is very few in comparison to the 361 studies they counted for valuation of travel time savings. In our review, we counted four empirical studies for interregional rail in the academic literature. First, Cascetta et al. (1996); Crisalli (1999); Nuzzolo et al. (2000), who applied a nested logit regression on a set of revealed preferences obtained on the Venice-Turin corridor in May 1995. Second, Rosenlind et al. (2001), who applied a multinomial logit regression on a set of stated preferences for two rail lines in Sweden (Stockholm-Sundsvall and Stockholm-Malmö). Third, Cascetta and Coppola (2012), who used a combination of RP and SP on the national rail network in Italy. Fourth, Chen and Souche Le Corvec (2019), who used two sets of RP obtained in 2016 and 2017 for the connection Paris-Bordeaux in France.

In addition, existing studies are quite brief in addressing the influence of the socioeconomic background of passengers on their valuations. Indeed, this question is essentially approached through the trip purpose (typically private versus business trips). This does not allow a comprehensive understanding of how much departure time suitability is worth to passengers.

Therefore, additional estimates for valuations of DTD reduction are required, especially to determine the influence of trip characteristics and socioeconomic background on those valuations. This work would enable improving travel demand forecast models that could better determine the demand for each train based on its socioeconomic characteristics. Similarly, detailed valuations would enable a better inclusion of departure time suitability in timetabling through welfare assessment, as presented in the next section.

1.3. Welfare assessment of timetables

Once valuations for DTD reduction are known, they can be used in socioeconomic assessments to help stakeholders take better decisions regarding capacity allocation. In this case, stakeholders want to compare several timetable scenarios with different departure times for the same trains. To do this, stakeholders usually agree on a reference scenario, and the other scenarios contain potential shifts in departure times. Then, the socioeconomic assessments are conducted for the timetable scenarios with comparison to the reference scenario.

To achieve a socioeconomic assessment, several methods can be used. First, a straightforward method consists of calculating the evolution of the generalised costs for both consumers and producers of a given product. The generalised cost for passengers is defined as a cost totalling all monetary (e.g. ticket price) and non-monetary elements involved in traveling (e.g. travel time) (Quinet and Vickerman, 2005a). The non-monetary elements are quantified as monetary elements using passenger valuations (cf. section 1.1). For departure time shifts in the timetable, consequences typically affect several characteristics of a rail connexion: in-vehicle time, feasibility of transfers, or shifts of departure/arrival time of passengers' trips. Then, these costs should be totalled over all possible connections concerned in the timetable. Regarding this, Svedberg et al. (2017) presented a practical formulation to evaluate these aggregated generalised cost for passengers and the operator costs of timetables. Similarly, Robenek et al. (2016, 2018) included the suitability of departure/arrival times in timetable optimisation through the aggregated generalised cost for rail passengers. However, using aggregated generalised costs has a poor accuracy in measuring socioeconomic benefits/losses because it does not account for the volume of passengers affected the changes in the timetable. Indeed, the aggregation of generalised costs consists of a simple sum, i.e. these costs are not weighted by corresponding passenger demand. Thus, the aggregated generalised cost does not accurately reflect the real socioeconomic costs of a timetable for society.

Furthermore, transport economists usually favour using cost-benefit analysis (CBA) framework (De Palma et al., 2011). In CBAs, valuations and travel demand forecast models are used to quantify differences in social costs and benefits between various scenarios to determine the optimal allocation of resources for the society. Instead of using generalised costs, CBAs rely on concepts of consumer and producer surpluses. Consumer surplus represents the socioeconomic gains/losses for consumers related to an allocation of economic resources. In this sense, it is expressed as "the area under the demand curve less the cost of production" (Quinet and Vickerman, 2005b). Therefore, consumer surplus not only accounts for the generalised cost experienced by passengers, but also considers demand affected by this cost. On the other hand, the producer surplus concept considers both production costs and revenues for producers (De Palma et al., 2011). Consequently, the producer surplus indirectly depends on the passenger volumes as well because producer revenues depend on ticket sales that are directly related to passenger volume. The total of consumer surplus, producer surplus, externalities, investment costs and government revenues, constitutes the total cost-benefit assessment called the *welfare*.

In the case of a departure time shift in rail timetables, calculating consumer and producer surplus is not straightforward. Indeed, this requires evaluation of the effect of departure time shifts on demand for each route using the timetable. One solution is to simplify the problem by assuming that demand remains constant after the departure time shift. This is the solution used by Ali et al. (2019), who proposed an efficient method to evaluate the welfare change corresponding to the accommodation of a commuter train path to a commercial train path. However, this work is only valid for frequent traffic and small departure time shifts, thus greatly limiting the applicability of the method.

To achieve a more general method, forecasting the evolution of passenger demand caused by departure time shifts is possible. To perform these calculations, a specific type of forecast model called schedule-based model should be used. Indeed, forecast models are commonly divided into two main groups: frequency-based models and schedule-based models. Frequency-based models use the frequency of a line to determine the average demand per vehicle for a given analysis period, e.g. during the afternoon peak. In these models, demand is evenly distributed to all vehicles of the timetable within the analysis period (Cascetta and Coppola, 2016). Such models are essentially used during the line planning stage (occurring before timetabling, cf. section 1.1) in order to plan the number of train departures on the line. However, because frequency-based models evenly distribute demand among vehicles, they are not able to determine the effect of specific departure times on the passenger demand for each train. On the other hand, schedule-based models consider each train of the timetable as part of an individual route with its own characteristics (e.g. ticket price, travel time, departure/arrival times) (Cascetta and Coppola, 2012). Using these characteristics and passenger preferences, schedule-based models assign demand to each individual route (and thus each individual train). More information on schedule-based models can be found in Wilson and Nuzzolo (2009).

Very few research papers tried to develop methods using schedule-based models to estimate the changes in welfare due to departure time shifts. So far, only Broman and Eliasson (2019) proposed a formulation to estimate welfare for interregional rail competition on departure times. Then, they used this formulation to test different principles for rail capacity allocation under different market conditions. However, this formulation relies on strong simplifications such as a uniform desired departure time distribution and the assumption that passengers only consider departures next to their desired departure times. Consequently, their method requires important improvements to be applicable in the timetabling process.

From this literature review, I concluded that there is a need to develop a general method to calculate the welfare changes corresponding to departure time shifts in any interregional rail timetable. Such a method should handle heterogeneous desired departure time distribution, multinomial choice of train departures, and consider an elastic demand in the welfare calculations. Developing such a method would contribute to improve allocation of rail resources and would thus help in creating a more sustainable transport system.

2. Research objectives

With the context presented in the introduction, I have two main objectives in this thesis. First, I aim at determining detailed valuations for DTD reduction in the case of interregional rail. Second, I aim at developing a method to evaluate the welfare consequences due to departure time shifts. These two objectives logically follow each other since the welfare assessment requires proper valuations for DTD reduction. I present the two objectives in more detail below.

2.1. Objective 1: Measurement of detailed valuation for departure time suitability

The first objective was to determine detailed valuation for DTD reduction in the case of interregional rail. Indeed, as presented in section 1.2, there is a need in the literature for additional studies on that issue. Especially, the current literature lacks detailed figures showing the influence of socioeconomic background of travellers on their valuations. This additional study will allow improving the inputs of schedule-based models and cost-benefit analysis.

2.2. Objective 2: Development of a general method for welfare assessment of departure time shifts in interregional timetables.

The second objective of this thesis is to develop a method that enables assessing the welfare change corresponding to departure time shifts in any interregional rail timetable. Indeed, as presented in section 1.3, the existing methods in the literature do not allow a proper inclusion of departure time suitability in timetabling for any interregional timetable. Our goal is to fill this gap with a new method that handles heterogeneous desired departure time distribution, multinomial choice of train departures, and consider an elastic demand in welfare calculation. This method would allow improving the current timetabling process (i.e. rail capacity allocation) by better inclusion of passengers' perspectives in the analysis.

3. Research methodology

The overall structure of the research methodology for this licentiate thesis is presented in Figure 4. To fulfil the first objective, we designed, implemented, and processed a stated-preference survey. I present this part in section 3.1. Regarding the second objective, we both conceived the welfare calculation method and illustrated this method with a case study. I present the design of the method in section 3.2. For the illustration with the case study, we built a schedule-based model using the valuations determined in our stated-preference survey. I also used these valuations in the welfare calculations for the case study. I detail this part in section 3.3.

3.1. Survey design, implementation and processing

3.1.1. Design of the stated-preference survey

To determine the detailed valuations for DTD reduction (our first research objective), we designed and conducted a SP survey on several Swedish interregional rail routes. We chose to conduct an SP survey rather than an RP survey due to the difficulties in acquiring RP data. Indeed, interregional rail is an open market in Sweden with several operators in competition. Therefore, the rail operators did not want to share their sensitive data with us.

For our SP survey, we designed a questionnaire divided in three parts. The first part involved acquisition of information about the current train ticket of the respondent and the trip characteristics. In this part, among other things, respondents provided their origin and destination, travel purpose, departure time, arrival time, and ticket price. The second part consisted of the SP choice tasks. In this part, levels of the SP choice tasks were calculated based on the answers to the questions in the first part. In the third and last part, respondents were asked about their socioeconomic background, e.g. gender, education or income level.

Our choices in the design of the SP choice tasks –design generation, attributes and their levels, number of alternative and choice tasks, and choice task layout – are detailed in our first paper Vautard et al. (2020b). We made these choices by considering state-of-the-art literature on orthogonal and efficient design (Bliemer and Rose, 2011; Walker et al., 2017), and on SP attributes and levels (Caussade et al., 2005; Fosgerau and Börjesson, 2015).

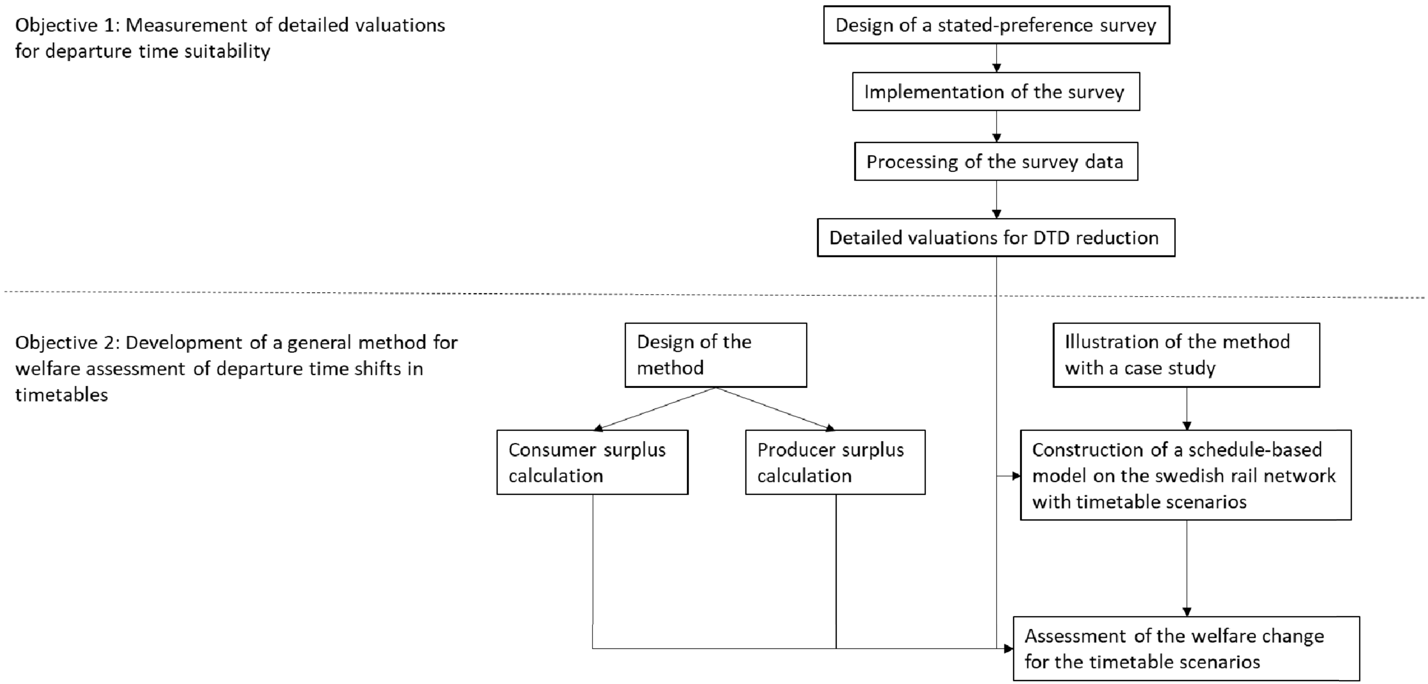

Figure 4: Overall structure of the research methodology.

I implemented the questionnaire on tablets using *SnapSurveys*. This choice allowed an automatic adaptation of the choice tasks' levels to the answers of the first part of the questionnaire. This was a key feature to improve readability of the choice tasks concerning departure time suitability.

Before deploying the survey at full scale, I conducted two pilot surveys to reduce potential bias and improve the quality of the results.

3.1.2. Implementation of the survey

I implemented our survey on three interregional rail routes in Sweden: Gothenburg−Stockholm, Skövde−Gothenburg and Gothenburg −Lund/Malmö. We chose these routes because they allowed covering different travel times, distances and passengers' profiles. This enabled determining the detailed effect of many background elements on valuations for departure time suitability.

I present the main characteristics of the chosen routes in Table 1. I show the location of the connected cities and the southern Swedish rail infrastructure in Figure 5.

Table 1: Main characteristics of the chosen field for the SP-survey, extracted from Vautard et al. (2020b).

Rail routes studied	***Railway distance***	***Shortest travel time***	***Number of direct trains per day***	***Number of different rail services***
Skövde–Gothenburg	144 km	1:02	36	6
Gothenburg–Lund/Malmö	284/300 km	2:01/2:13	24	2
Gothenburg–Stockholm	455 km	2:56	35	3

Figure 5 : Locations of Malmö, Lund, Gothenburg, Skövde and Stockholm in southern Sweden and the studied rail routes, extracted from Vautard et al. (2020b)

For simplification, I interviewed only passengers going from and to the terminal stations. Unfortunately, the rail operators did not allow us to interview passengers inside the trains. Consequently, I interviewed passengers on train platforms inside the stations in Skövde and Gothenburg. Our strategy was to propose the questionnaire to as many passengers as possible before each train departure. Therefore, the selected respondents were those who agreed to answer and had time to finish the questionnaire (5 minutes on average). I conducted the survey on several Tuesdays and Wednesdays in October and November 2018. I covered departures from 5.30 to 18.00 to include both peak periods and the midday off-peak.

These field conditions may introduce a bias in the survey due to exclusion of certain respondents: passengers boarding the train at the last minute, slow-answering respondents, certain disabled passengers (e.g. blind persons) or non-Swedish-speaking passengers. However, excluding these passengers is a reasonable compromise to achieve the survey without greatly affecting the results.

In the end, we obtained 552 respondents in our survey, and the sample composition is balanced in most aspects. The only exceptions are found for the distance travelled and the education level. Indeed, a major part of our sample consists of travellers between Stockholm and Gothenburg, and these respondents mostly have taken higher education. More details about the sample composition are presented in Vautard et al. (2020b).

3.1.3. Survey data processing

Once I finished the fieldwork, I applied several multinomial logit (MNL) regressions to the data. In these regressions, I partitioned the sample according to various socioeconomic aspects or trips characteristics, e.g. trip purpose or income level. I used the utility functions presented in Equation 1 for the left alternative in the choice tasks, and Equation 2 for the right alternative.

$$V_1 = \beta_{TP} * TP_1 + \sum_s \left[\delta_{p,s} * (\beta_{TT,s} * TT_1 + \beta_{DTDE,s} * DTDE_1 + \beta_{DTDL,s} * DTDL_1)\right] \quad \text{Equation 1}$$

$$V_2 = ASC_2 + \beta_{TP} * TP_2 + \sum_s \left[\delta_{p,s} * (\beta_{TT,s} * TT_2 + \beta_{DTDE,s} * DTDE_2 + \beta_{DTDL,s} * DTDL_2)\right] \quad \text{Equation 2}$$

V denotes the deterministic part of the utility, *s* the index for each segmentation category, $\delta_{p,s}$ the Boolean indicator being equal to one if passenger *p* belongs to the segmentation category *s*, *TT* is travel time, *TP* is the ticket price, *DTDE* the departure time displacement for earlier trips, and *DTDL* the departure time displacement for later trips. β elements are the MNL coefficients, and ASC_2 is the alternative specific constant for the second alternative.

I used *BisonBiogeme* (Bierlaire, 2003) to apply the MNL regressions to the sample. I expressed the results found in three different manners: regression coefficients, willingness to pay (WTP) and time multipliers. More details about the data processing can be found in the paper Vautard et al. (2020b).

3.2. Design of the method for welfare assessment

The second objective of the licentiate is to develop a method that enables assessing the welfare change corresponding to departure time shifts in any interregional rail timetable. To do this, I bridged the use of schedule-based models with the cost-benefit analysis framework. This methodology enables forecasting the detailed impact of departure time shifts on the passenger demand, thus enabling the calculation of consumer and producer surplus with an elastic demand. In my approach, the desired departure time distribution is not considered uniform as in Broman and Eliasson (2019), and all train departures are considered by passengers regardless of their desired departure time.

Regarding welfare calculation, we assumed that external effects provoked by departure time shifts are negligible in comparison to consumer and producer surpluses. Therefore, only consumer and producer surplus are included in the welfare calculation.

3.2.1. Schedule-based models and demand forecast

When a departure time is shifted, the consequences on passenger trips can be multiple, e.g. reduced in-vehicle times, missed connections, or shifts in departure times for the trips. To capture all these effects, schedule-based models estimate passenger route choices at the *path* level. A path can be defined as the sequence of trips that transport a passenger from his/her origin to his/her destination. Each trip of the sequence is called a *path leg*. I show an example of path and its path legs in Figure 6.

Figure 6: An example of a path including two path legs using rail, extracted from Vautard et al. (2020).

In schedule-based models, total rail demand is commonly obtained through the first three steps of the four-step models. Total rail demand is then assigned to each path based on its generalised cost. The general formulation of the generalised cost of a path is shown in Equation 3.

$$GC_{pth,ddti,s} = WTP_{DTDE,s} * DTDE_{pth,ddti} + WTP_{DTDL,s} * DTDL_{pth,ddti} + PC_{pth,s} \quad \text{Equation 3}$$

$WTP_{DTDE,s}$ and $WTP_{DTDL,s}$ refers to the willingness to pay for respectively shorter DTDE and DTDL. $PC_{pth,s}$ represents the perceived costs of the path *pth* that are unrelated to scheduling. An example of $PC_{pth,s}$ is presented in the next section.

To assign total rail demand, knowing the distribution of desired departure times is required. This distribution can be obtained in a discretised form through travel surveys. I denote $G^s(ddti)$ as the function that returns the number of passenger of the demand segment s having a desired departure time interval *ddti*.

Once the desired departure time distribution and generalised costs are known, the total rail demand can be assigned to each route through a choice model. With this method, the demand for a path *pth* for the passengers having a desired departure time interval *ddti* and belonging to the demand segment *s* is expressed as in Equation 4.

$$D_{pth,ddti,s} = P_{p\in\{s,ddti\},pth} * G^{s}(ddti) \qquad \text{Equation 4}$$

With $P_{p\in\{s,ddti\},pth}$ being the probability that a passenger *p* belonging to demand segment s and having a desired departure time interval *ddti* choses the path *pth*. This probability is obtained with a discrete-choice model, e.g. the MNL model, applied to the generalised cost presented in Equation 3.

3.2.2. Consumer surplus calculation

Once demand and generalised costs are known, consumer surplus can be estimated. Consumer surplus is commonly obtained through the rule-of-a-half, which relies on the assumption of a local linearity of the demand function (Quinet and Vickerman, 2005c). However, in our situation, consumer surplus cannot be defined at the path level in most situations. Indeed, the departure time shift of trains can lead to creation or removal of paths, thus removing the possibility to track a path in both situations, i.e. before and after the departure time shift. To solve this issue, we propose to aggregate the calculation at the origin-destination (OD) level. In this case, we can calculate demand and generalised cost of the collection of paths connecting a specific OD pair. We calculate demand by totalling the demand for all paths in the collection. Concerning generalised cost, we propose to calculate it through a weighted average of the generalised costs of the paths in the collection, with the weights corresponding the demand for each path.

However, this method does not enable calculating the usual consumer surplus. Indeed, our method only enables defining a similar indicator in a context where the usual consumer surplus cannot be used. Therefore, to be fully transparent, we call our estimation the *pseudo consumer surplus*. It is expressed in Equation 5 using the rule-of-a-half. In our case study (cf. section 3.3), we investigate if this indicator can provide relevant socioeconomic outcomes.

$$\begin{aligned}\Delta_{1\to 2}CS_{od,ddti,s} = \frac{1}{2} * &\left(\sum_{pth_{od}\in S_1} D_{pth_{od},ddti,s} + \sum_{pth_{od}\in S_2} D_{pth_{od},ddti,s} \right) \\ &* \left(\frac{\sum_{pth_{od}\in S_1} D_{pth_{od},ddti,s} GC_{pth_{od},ddti,s}}{\sum_{pth_{od}\in S_1} D_{pth_{od},ddti,s}} \right. \\ &\left. - \frac{\sum_{pth_{od}\in S_2} D_{pth_{od},ddti,s} GC_{pth_{od},ddti,s}}{\sum_{pth_{od}\in S_2} D_{pth_{od},ddti,s}} \right)\end{aligned} \qquad \text{Equation 5}$$

With $pth_{od} \in S_1$ referring to the index of the paths connecting the OD pair *od* that exist in situation one; the similar applies to $pth_{od} \in S_2$ for paths existing in situation two.

3.2.3. Producer surplus calculation

Concerning producer surplus, we simplified its estimation by assuming that ticket prices and production costs are not affected by the departure time shifts. This hypothesis is consistent with the fact that the shifts considered during timetabling are generally small, and should therefore not significantly affect operational constraints. With this simplification, producer surplus consists of the changes in ticket revenues that are directly related to the changes in the demand for each path. The subsequent expression of the producer surplus for a demand segment s is expressed in Equation 6.

$$\Delta_{1\to 2}PS_s = \sum_{pth \in S_2} D_{pth,s} * F_{pth,s} - \sum_{pth \in S_1} D_{pth,s} * F_{pth,s} \qquad \text{Equation 6}$$

With $D_{pth,s}$ being the demand for the path *pth* from the demand segment s, and $F_{pth,s}$ the total fare for the path, which consists of the sum of the fares of each path leg of the path.

3.3. Illustration of the method with a case study

In order to illustrate our method, we illustrated our welfare calculation in a case study. This case study consisted of a simple departure time shift on the busiest interregional rail line in Sweden between the cities of Stockholm and Gothenburg.

To achieve this, I implemented a schedule-based model in *PTV VISUM* that covered the entire Swedish national rail network. This model forecasted the assignment of total rail demand over the suitable paths. In this model, we disregarded the constraint of vehicle capacity for simplification. Regarding the inputs, I imported the rail network as GTFS data. For the total rail demand, I used the output of the national Swedish model *Sampers*. Concerning the desired departure time distribution, I used the distribution obtained in the Swedish national travel survey of 2011-2014. Finally, I took the valuations from Trafikverket (2018) and Vautard et al. (2020b). In addition, I considered two demand segments: private trips and business trips.

I calculated the generalised cost by totalling the fare, suitability of departure times, and perceived journey time. Perceived journey time is a common concept that includes all the time components of a path in addition to the common in-vehicle time. This concept is expressed as in Equation 7 (PTV AG, 2019).

$$PJT_{pth} = \sum_{pl \in pth} TT_{pl} + \sum_{tr \in pth} (M_{WT} * WT_{tr} + M_{Trt} * Trt_{tr}) + M_{Ac} * Ac_{pth} + M_{Eg} * Eg_{pth} + M_{AuxT} * AuxT_{pth} + M_{OWT} * OWT_{pth} + * TrP * NT_{pth}$$ Equation 7

With $pl \in pth$ as the index for the collection of path legs that are part of the path *pth*, TT_{pl} the travel time of the path leg *pl*, $tr \in pth$ the index for the collection of transfers included in the path *pth*, WT_{tr} the transfer walking time of transfer *tr*, Trt_{tr} the transfer waiting time of transfer *tr*, Ac_{pth} the access time of path *pth*, Eg_{pth} the egress time of path *pth*, $AuxT_{pth}$ the auxiliary ride time of path *pth*, OWT_{pth} the origin wait time of path *pth*, NT_{pth} the number of transfers of path *pth*, and *TrP* the transfer penalty constant. The *M* coefficients are the valuations for each component expressed as time multipliers.

Consequently, we defined the perceived costs (other than scheduling) in our case study as expressed in Equation 8.

$$PC_{pth,s} = VoT_s * PJT_{pth} + \sum_{pl \in pth} F_{pl,s}$$ Equation 8

With *VoT* being the valuation of in-vehicle time and F_{pl} the fare of the path leg *pl*.

Our timetable modification consisted of a shift in the departure time of the busiest train in the morning peak between Stockholm and Gothenburg. I shifted the departure time of this train to 30 minutes earlier. For a more understandable presentation of the results, I focused the estimation for the OD pair with the highest demand, i.e. for the 66 passengers going from central Stockholm to central Gothenburg. For this OD, I calculated the change in pseudo consumer surplus for each desired departure time interval and the producer surplus change for each path. These results are presented in Vautard et al. (2020).

4. Scientific contributions

4.1. Paper 1 - Estimation of interregional rail passengers valuations for their desired departure times

In paper 1, I focused on our first research objective. In this paper, we present the survey that we implemented to determine valuations for DTD reduction (cf. section 3.1), and we present the results found.

The main contribution of this paper consists of the figures obtained for the valuations through the survey. Most of them were statistically significant, and several elements support the validity of our findings. First, the valuations found for the control groups are consistent with our expectations. Second, the valuations for travel time savings that I found are within the same order of magnitude as the reference literature (i.e. Trafikverket (2018)). These valuations are also consistent with the literature for a large majority of the partitions of the sample. Only the valuations found for private trips, leisure trips, midday trips and young travellers highlighted potential bias in the method for these respondents.

In addition, most of our findings show that the difference between the passenger categories among most partitions is statistically significant. The only insignificant behavioural differences that I found were for trip distance, household size, gender and education level. This may be due to having too small a sample size. Our results, however, do not enable fully concluding about the influence of socioeconomic background and trip characteristics on the valuations for DTD reduction (cf. section 5.2).

Our results also highlight a great diversity in valuations for DTD reduction. Indeed, I found time multipliers ranging from 0.1 to 0.719. Passengers with high time multipliers are the morning travellers, business passengers, seniors, parents, and middle-income travellers. These types of passenger have very constrained schedules. On the other hand, low time multipliers are found for low-income travellers, female travellers, passengers aged between 25 and 44, and two-person households. These types of passengers are much more flexible in their planning.

Our findings show that departure time adjustments are always valued less than in-vehicle time. This sounds logical to us since a rational traveller should prefer to spend his/her time doing activities at their origin/destination instead of spending the same amount of time travelling in a vehicle. However, some literature found time multipliers greater than one for departure time suitability.

This fact, surprised us, and may be explained by the different data collection methods (RP or SP, or the choice tasks' layout) or differences in the acquisition of respondent's desired departure time.

4.2. Paper 2 - Welfare assessment of departure time shifts in interregional rail timetables

In paper 2, I focused on our second research objective. In this paper, we present our proposition to determine the welfare changes for a departure time shift in any interregional rail timetable (cf. section 3.2). We also present the illustration of the method through the case study on the line between Stockholm and Gothenburg (cf. section 3.3).

The main contribution of this paper is the description of our method where we manage to bridge the knowledge in schedule-based models with welfare assessments. With this solution, we provide a more general and more advanced method than those existing in the literature. Indeed, our method allows considering an elastic demand for each possible path using the trains of the timetable. This better reflects passengers' perspectives than when using aggregate generalised costs proposed by Robenek et al. (2016, 2018) and Svedberg et al. (2017). Our method can also be used for any interregional rail timetable.

Our case study shows a concrete example of how our method can be used to determine the most beneficial timetable. Indeed, I have measured that our scenario with the departure time shift of 30 minutes earlier would cause a net total loss of welfare of SEK -317, with an average loss of four Swedish krona per passenger. Moreover, our case study highlights the capability of our method to deliver a detailed analysis of equity aspects. Truly, I showed that the welfare loss was essentially supported by passengers departing between 6:30 and 8:50. On the other hand, passengers departing between 5:40 and 6:30 were slightly benefited by the departure time shift.

5. Conclusions and future directions

5.1. Contributions of the thesis

Rail capacity allocation processes are currently in need of improvements to face increasing traffic. In this thesis, I propose a solution to this issue through inclusion of passengers' perception of departure time suitability in timetable planning. Such inclusion would contribute to optimize rail capacity allocation according to passengers' perspectives in timetables. To achieve this, two challenges needed to be solved. First, proposing a detailed measurement of valuations of departure time suitability for interregional passengers. Second, developing a general and applicable method for welfare evaluation of timetables in the case of departure time shifts. With the two research papers of this thesis, I fulfilled both research objectives, thus providing rail planners with the valuations and the method needed to improve timetable planning.

Concerning the first objective, I determined detailed valuations for DTD reduction through a SP survey on several Swedish interregional lines. Before our study, only a few and brief research work had been conducted on this topic. The figures found show a great diversity in passenger valuations, thus improving understanding in passengers' behaviours towards departure time suitability. In addition, detailed figures are now available for rail planners. These figures can be used as inputs for schedule-based models and cost-benefit analysis. However, due to the limitations in the methodology (cf. section 5.2), our results can only be used as first approximation if the DTDs involved are around 60 minutes, say, intuitively between 30 and 90 minutes.

Regarding the second research objective, I succeeded in improving the current methods comparing timetables in terms of welfare. Indeed, I proposed a more general and advanced method than those existing in the literature. In addition, this method even allows a detailed look at the equity effects of different timetable scenarios. Consequently, I invite rail planners to make use of this method to include departure time suitability in timetabling process. For instance, rail planners can use this method to better allocate capacity on Swedish lines where procured traffic and commercial traffic use the same tracks. This would help better solve the increasing conflicts in these specific cases where capacity allocation issues arise more often. However, because of the limitations in this approach (cf. section 5.2), I recommend a careful use of my method in timetabling. For instance, to start with I suggest using my method to solve non-critical choices (e.g. cases with hesitations or minor conflicts).

5.2. Limitations

This thesis work is not exempt from limitations. Starting with the survey work, several elements should be highlighted. First, the fact that I used only DTDs of plus or minus 60 minutes in the design of SP choice tasks does not allow studying the potential non-linearity of the valuations. Second, the presence of certain survey biases could affect the validity of the findings. Indeed, I noted that certain respondents had difficulties in connecting the choice tasks to their current trip situation. In addition, since the respondents were on the verge of boarding their trains, their flexibility in trip planning at this moment was probably lower than when they booked their train ticket. Moreover, the data processing is also not exempt from certain limitations. First, we did not account for correlation among observations from the same respondents in our regressions. Regarding this, we managed to rerun a mixed-logit regression on our survey after the article was sent. The results obtained are very similar, so this limitation is not critical. Second, the small sample size and the difficulty of correlating the SP alternatives to the four variables under study makes it hard to control for the interactions between socioeconomic variables and trip characteristics in our regressions. However, this second limitation only restricts the validity of our findings to explain different behaviours towards scheduling flexibility. Our findings remain valid for use as inputs of demand forecast models and cost-benefit analysis.

Concerning the welfare assessment method, several limitations exist as well. First, using a pseudo consumer surplus does not allow exact estimation of usual consumer surplus. Nevertheless, in our view, this approximation is the best compromise that allows estimation of welfare change for any departure time shift, where the usual consumer surplus cannot be defined in most cases. Second, the valuations used by schedule-based models are not necessarily linear, as mentioned in the previous paragraph. Third, a correlation exist between (perceived) journey time and departure time in schedule-based models. This is not the case in the modelling framework in which valuations of DTD reduction are evaluated. Although this is generally disregarded in schedule-based modelling, this issue may generate biases in our welfare calculations. Finally, the difficulty in gathering quality inputs for the schedule-based models and the time required to build such models might restrict using our method in real situations.

5.3. Future research

The limitations described call for future research to resolve them. For instance, we suggest that a survey similar to ours be conducted with passengers at the instance of their ticket purchase. This would help to better account for constraints on trip schedules in answers to SP choices in comparison with conducting the survey on train platforms. In addition, we recommend that future research should be directed towards questioning the non-linearity of the valuations for DTD reduction. For example, I suggest the implementation of surveys with a similar design but using DTDs of 30 minutes or 90 minutes, and the results should be compared with our survey using DTDs of 60 minutes.

Furthermore, we suggest using a mixed-logit regression instead of the standard MNL to account for the correlation among observations from the same respondents. In addition, in order to better control for the interactions between socioeconomic variables and trip characteristics, we recommend a larger sample size in future surveys, and we suggest that future research should be oriented correlating SP alternatives to more than two variables in SP data processing.

Moreover, the comparison of valuations found to the literature highlighted a need to establish a standardised method for assessment of valuations for DTD reduction. This is especially true regarding acquisition of desired departure time of passengers. This could help to understand why time multipliers greater than one are found in the literature.

Concerning the development of schedule-based models, future research should target lowering the difficulty in gathering quality inputs. In particular, I recommend finding ways to simplify estimating desired departure time distribution for the different demand segments. Besides this aspect, future research should study how to include the correlation of total journey time with departure time (regardless of travel time reliability) in the acquisition of the valuations for DTD reduction. Regarding this aspect, plenty of research has been conducted focusing on car traffic, where travel time is related to congestion that is related to departure time. Parts of this literature may be adapted to interregional public transport, where the relation between departure time and availability of transfers is crucial. For instance, Arellana et al. (2012) provides a method to create efficient SP surveys where departure time and travel time are dependent to each other.

On top of that, I recommend orienting future research towards improving the pseudo consumer surplus indicator or the development of better indicators. Such indicator should be as applicable as the pseudo consumer surplus, but aiming for better accuracy.

Finally, a last idea for future research could be to use a different method to evaluate the consumer surplus of a timetable. For instance, agent-based models could be used to track each passenger's choice of route using the timetable.

Then, the change in generalised cost for each passenger could be estimated and the total of these costs would provide the consumer surplus.

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