Welfare assessment of departure time shifts in interregional rail timetables

Authors

Félix Vautard, PhD student[a] (felix.vautard@abe.kth.se)

Chengxi Liu, Researcher[b] (chengxi.liu@vti.se)

Oskar Fröidh, Associate Professor[a] (oskar.froidh@abe.kth.se)

[a] KTH Royal Institute of Technology, Division of transport planning, Brinellvägen 23, SE-100 44 Stockholm, Sweden

[b] VTI, the Swedish National Road and Transport Research Institute, Malvinas väg 6, 114 28 Stockholm, Sweden

Corresponding author

Félix Vautard, felix.vautard@abe.kth.se, +46 8 790 70 54. KTH Royal Institute of Technology, Division of Transport planning, Brinellvägen 23, SE-100 44 Stockholm, Sweden.

Keywords

Departure time choice; Timetable optimisation; Schedule-based model; Welfare; Consumer surplus; Producer surplus; Cost-benefit analysis.

Abstract

In order to improve current rail timetabling process, the suitability of train departure times for passengers could be included in timetable optimisation. To achieve this, one possibility is to calculate the consumer and producer surplus (i.e. the welfare) coming from departure time shifts in a rail timetable. However, the existing methods for welfare calculation are not directly applicable to any interregional rail timetable. To fill this gap, we propose a new method in the current paper. This method enables the comparison of any interregional rail timetable within the cost-benefit analysis framework while considering an elastic demand. Our method takes advantage of schedule-based models that allow considering the impact of departure time shifts on each individual route at a specific time of the day. We illustrate this method on a case study on a Swedish interregional line. The case study shows the usefulness of the method to determine the efficiency of rail capacity allocation. Unfortunately, the great amount of data and work required to implement our method might restrict its usage. Future research should be directed towards solving this limitation.

1. Introduction

Improving rail transport should play a central role in developing sustainable transportation systems. In this respect, rail timetables should be well designed to make rail more attractive than the other transport modes (Lundqvist and Mattsson, 2001). Unfortunately, there is a discrepancy today between the current practices in timetabling and the complexity of passengers' preferences (Parbo et al., 2016). For example, the suitability of departure and arrival times for passengers is not included in timetabling today. The suitability of departure and arrival times refers to how well the timetable design allows to reduce the disutility experienced by passengers when they are forced to adapt their activities to the train schedules. Including this element in timetabling should lead to improvement of interregional rail timetables.

One way to include this aspect is to calculate the consumer and producer surplus (i.e. the welfare) coming from departure time shifts in a rail timetable. To this end, the changes on the available routes, their generalised cost and their passenger demand should be assessed. To do this, schedule-based demand forecast models can be used. These models rely on the classical four-step structure with each individual train being considered as part of a route with its own characteristics for the route assignment (Cascetta and Coppola, 2012; Wilson and Nuzzolo, 2009).

Only a few research works tried to develop methods using schedule-based models to estimate the changes in welfare due to departure time shifts. First, Broman and Eliasson (2019) proposed a formulation to estimate the welfare to handle interregional rail competition on departure times. However, their formulation relies on strong simplifications such as a uniform desired departure time distribution and the assumption that passenger only consider departures next to their desired departure times. Second, Svedberg et al. (2017) presented a practical formulation to evaluate the aggregated generalised cost and the operator costs of timetables. Nevertheless, they also assumed that passengers consider only the two closest departures times. In addition, the aggregated generalised cost does not account for the passenger demand concerned by the timetable changes. Third, Ali et al. (2019) proposed an efficient method to evaluate the welfare change corresponding to the accommodation of a commuter train path to a commercial train path. Nonetheless, their method is only applicable to small changes in the timetable for frequent commuter trains. Finally, Robenek et al. (2016, 2018) included the suitability of departure/arrival times in timetable optimisation through the aggregated generalised cost for rail passengers. The asset of this method is that passenger perspectives are directly included in a timetable optimisation algorithm. The drawback of this method, though, is that it considers only the aggregated generalised costs, which brings the same limitation than Svedberg et al. (2017).

To fill the limitations of the existing literature, we propose in this paper a method to evaluate the welfare change corresponding to departure time shifts in any interregional rail timetable. Such method enables the comparison of any interregional rail timetable within the cost-benefit analysis framework while considering an elastic demand. In addition, we illustrate the applicability of our method through a case study on a Swedish interregional line. This research work intends to be incorporated in timetable optimisation methods to improve the current timetabling processes.

2. Proposed method

2.1. Schedule-based models and demand estimation

As presented in the previous section, schedule-based models are commonly used to determine the distribution of the demand over an analysis period (typically a workday) and the generalised costs of different routes. These models rely on the concept of *schedule delay (SD)*, defined as the time difference between a passenger's desired departure time and a timetabled departure (Douglas and Miller, 1974). As explained in Vautard et al. (2019), we chose to rename the concept of schedule delay as *departure time displacement (DTD)* to avoid the confusion with the usage of schedule delays to study travel time reliability. It is common to separate the DTD into two components to account for asymmetric preferences: the *Departure Time Displacement Earlier* (DTDE) for earlier departures than desired, and the *Departure Time Displacement Later* (DTDL) for later departures than desired.

Such concept, however, does not fully capture the effects of departure time shifts for passengers. Indeed, most of train trips are part of a sequence of trips that together defines the route that leads a passenger from his/her origin to his/her destination. This route is commonly called a *path* in transport modelling. Each trip element of the path (e.g. walking to a bus stop) is named a *path leg*. An example of a path and its path legs is illustrated in Figure 1.

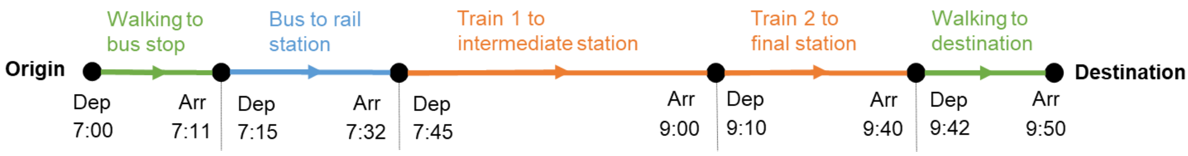

Figure 1: An example of a path including two path legs using rail

Knowing this, a shift in the departure time of a train may greatly affect the path legs connected to this shifted departure. We illustrate the potential complexity of the consequences on Figure 2. On this figure, the departure time of the first train of the previous example (Figure 1) is shifted 15 minutes later.

To include these effects, the schedule-based models extend the DTD concept to paths. In this case, the DTDE and DTDL refers to the departure time at the origin of the path, and each passenger must choose between several paths that include one or several train departures. The corresponding utility function of each path is expressed as in Equation 1.

$$V_{pth,p\in s} = \beta_{DTDE,s} * DTDE_{pth,p} + \beta_{DTDL,s} * DTDL_{pth,p} + PE_{pth,p} \qquad \text{Equation 1}$$

Here *pth* denotes the index of the path. $DTDE_{pth,p}$ is the DTDE for path *pth* and passenger *p*; it is expressed as $DTDE_{pth,p} = \max(0, DDT_p - DT_{pth})$, where DT_{pth} is the departure time of path *pth* and DDT_p the desired departure time of passenger *p*. Similarly, $DTDL_{pth,p} = \max(0, DT_{pth} - DDT_p)$. $PE_{pth,p}$ refers to the other elements related to the path *pth* and perceived by passenger *p* (e.g. in-vehicle times, comfort levels or ticket prices).

In schedule-based models, the demand is commonly determined using multinomial logit (MNL) models. In the MNL models, the choice probability of the passenger *p* to choose a path is expressed as in Equation 2.

$$P_{p\in\{s,ddti\},pth} = \frac{e^{V_{pth,p\in\{s,ddti\}}}}{\sum_{j\in J} e^{V_{j,p\in\{s,ddti\}}}} \qquad \text{Equation 2}$$

Here the notation $p \in \{s, ddti\}$ means that the passenger *p* belongs to the demand segment *s* and has a desired departure time belonging to the desired departure time interval *ddti*. *J* refers to the collection of all available paths connecting a given origin-destination (OD) pair.

In order to calculate the demand using the previous choice model, the distribution of desired departure times among the rail passengers should be used. Such distribution can be estimated from passenger alighting/boarding data or travel surveys. Once this distribution is known, the number of rail passengers having as desired departure time the particular time *t* can be calculated by simply multiplying the total rail demand by the probability density function. The total rail demand is commonly obtained through the first three steps of the four-step models.

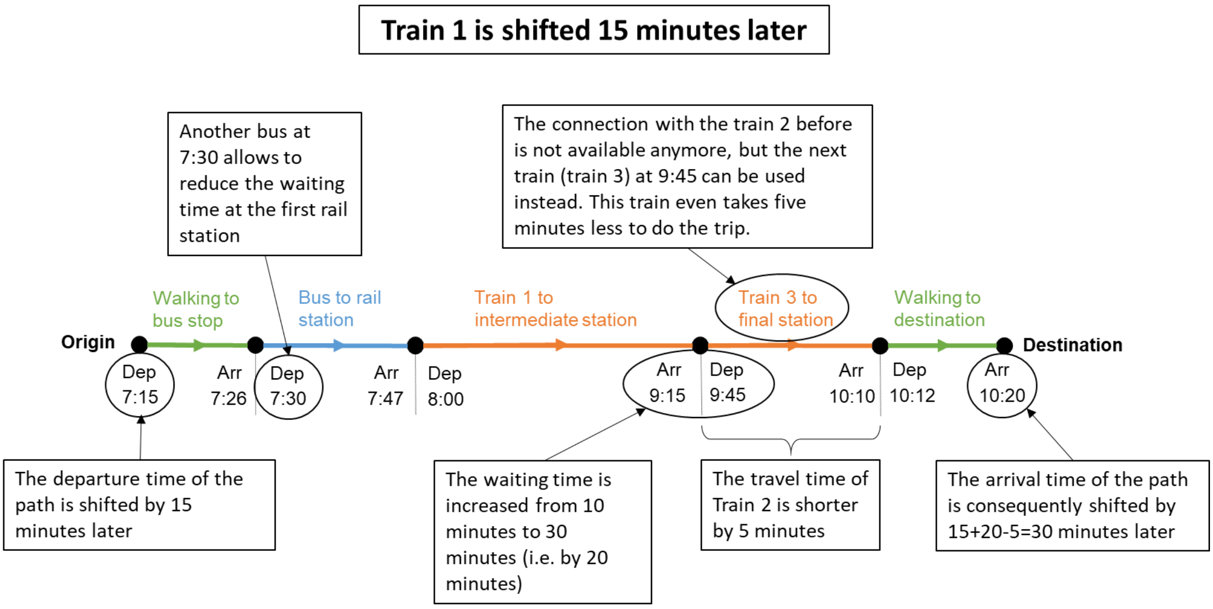

Figure 2: Illustration of the consequences of a departure time shift on the path of Figure 1

We denote the demand function $g^s(t)$ that returns the number of passengers of the demand segment *s* having a desired departure time *t*. In practice, the continuous function of $g^s(t)$ is difficult to obtain and manipulate. Therefore, the density function is usually discretised by time intervals (e.g. 8:00-8:05). We denote the discrete function as $G^s(ddti)$, with *ddti* being a desired departure time interval.

Finally, the demand for the path *pth* is obtained through Equation 3.

$$D_{pth,ddti,s} = P_{p\in\{s,ddti\},pth} * G^s(ddti) \qquad \text{Equation 3}$$

2.2. Consumer surplus evaluation

By dividing the utility function presented in Equation 1 by the cost coefficient, the generalised cost of a path *pth* can be expressed as in Equation 4. This generalised cost is perceived by passengers belonging to the demand segment *s* and having the desired departure time belonging to the interval *ddti*.

$$GC_{pth,ddti,s} = WTP_{DTDE,s} * DTDE_{pth,ddti} + WTP_{DTDL,s} * DTDL_{pth,ddti} + PC_{pth,s} \qquad \text{Equation 4}$$

$WTP_{DTDE,s}$ and $WTP_{DTDL,s}$ refers to the willingness to pay for respectively shorter DTDE and DTDL. $PC_{pth,s}$ represents the other perceived costs of the path *pth* that are unrelated to scheduling (i.e. $PC_{pth,s} = \frac{PE_{pth,p\epsilon s}}{\beta_{TP}}$). An example of $PC_{pth,s}$ is presented in our case study (section 3.1).

To simplify welfare calculations, the demand curve is usually considered to depend linearly on the generalised cost. Assuming this linearity, the change in consumer surplus can be expressed using the rule of a half (Quinet and Vickerman, 2005). In our situation, the shift of one or several train departure times can lead to the creation or removal of several suitable paths. This non-linear phenomenon makes it impossible to use the rule of a half at the path level. However, we can consider as “product” for the consumer surplus the set of paths connecting a specific OD pair in situation one and two. The demand for this set of path is obtained by summing of the demand for each path of the set. Regarding the generalised cost of the set, we propose to aggregate the generalised cost of each path with a weighted average using the demand for each path as weight. This aggregated generalised cost for an OD pair is presented in Equation 5.

$$GC_{od,ddti,s} = \frac{\sum_{pth_{od}} D_{pth_i,ddti,s} GC_{pth_{od},ddti,s}}{\sum_{pth_{od}} D_{pth_{od},ddti,s}} \qquad \text{Equation 5}$$

Here pth_{od} refers to a path connecting the OD pair *od*. $D_{pth_{od},ddti,s}$ refers to the demand expressed in Equation 3, and $GC_{pth_{od},ddti,s}$ refers to the generalised cost of a path expressed in Equation 4.

We can now use the rule of a half to obtain the consumer surplus for the OD pair *od*, the desired departure time interval *ddti* and the demand segment *s* as in Equation 6.

$$\begin{aligned}\Delta_{1\to 2} CS_{od,ddti,s} = \frac{1}{2} * &\left(\sum_{pth_{od} \in S_1} D_{pth_{od},ddti,s} + \sum_{pth_{od} \in S_2} D_{pth_{od},ddti,s} \right) \\ &* \left(\frac{\sum_{pth_{od} \in S_1} D_{pth_{od},ddti,s} GC_{pth_{od},ddti,s}}{\sum_{pth_{od} \in S_1} D_{pth_{od},ddti,s}} - \frac{\sum_{pth_{od} \in S_2} D_{pth_{od},ddti,s} GC_{pth_{od},ddti,s}}{\sum_{pth_{od} \in S_2} D_{pth_{od},ddti,s}} \right)\end{aligned} \qquad \text{Equation 6}$$

Here $pth_{od} \in S_1$ refers 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.

Finally, to obtain the total change in consumer surplus between two timetables, the figure obtained in Equation 6 should be summed over all the ODs, all the desired departure time intervals and all the demand segments under consideration.

2.3. Producer surplus evaluation

In a first approach, we assume that fares and production costs do not vary with the shifts in departure times. This hypothesis is relevant when shifts are small enough so that they do not affect significantly the operational constraints (e.g. crew scheduling or vehicle circulation). With this hypothesis, the producer surplus simply corresponds to changes in revenues (due to changes in the demand) for each path. Therefore, the producer surplus change for one demand segment *s* can be expressed as in Equation 7. Finally, this figure should be summed over all demand segment to obtain the total producer surplus change.

$$\Delta_{1\to 2} PS_s = \sum_{pth \in S_2} D_{pth,s} * F_{pth,s} - \sum_{pth \in S_1} D_{pth,s} * F_{pth,s} \qquad \text{Equation 7}$$

With $D_{pth,s}$ the demand for the path *pth* from the demand segment *s* and expressed as $D_{pth,s} = \sum_{ddti} D_{pth,ddti,s}$. Also, $F_{pth,s}$ denotes the total fare for the path, and consists of the sum of the fares of each path leg of the path.

3. Case study

3.1. Model description

To illustrate the welfare calculations presented in section 2, we test our method on a simple departure time shift on the Swedish busiest interregional rail line between Stockholm and Gothenburg cities.

To achieve this, we implemented in *PTV VISUM* a schedule-based model over the Swedish national rail network. For the inputs, we imported the rail network from GTFS data and the total rail demand from the forecasts obtained by the national Swedish model called Sampers. Also, we used the desired departure time distribution obtained in the Swedish national travel survey of 2011-2014, and we took the valuations from the literature (Trafikverket, 2018; Vautard et al., 2019). Finally, we consider two demand segments: private trips and business trips.

In our case study, we calculated the generalised cost of a path through the sum of the fare, the suitability of the scheduling and the perceived journey time. The perceived journey time is an extension of the in-vehicle time that includes the other time components of the paths. This concept is expressed as in Equation 8 (PTV, 2020).

$$PJT_{pth} = \sum_{pl \in pth} TT_{pl} + \sum_{tr \in pth} (M_{WT} * WT_{tr} + M_{Trt} * Trt_{tr}) + M_{Ac} * Ac_{pth} + M_{Eg} * Eg_{pth} + M_{AuxT} * AuxT_{pth} + M_{OWT} * OWT_{pth} +* TrP * NT_{pth} \quad \text{Equation 8}$$

With $pl \in pth$ the index for the collection of path legs being 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.

Based on the definition of the perceived journey time in VISUM, we defined the perceived costs (other than scheduling) in our case study as in Equation 9.

$$PC_{pth,s} = VoT_s * PJT_{pth} + \sum_{pl \in pth} F_{pl,s} \quad \text{Equation 9}$$

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

3.2. Timetable scenario and results

We chose to test our method on a simple scenario with one departure time shift. In this scenario, we shifted the busiest train in the morning peak between Stockholm and Gothenburg by 30 minutes earlier. We present here the results obtained for the OD pair with the highest demand, i.e. for 66 passengers from central Stockholm to central Gothenburg.

In Figure 3, we show the evolution of the consumer surplus per desired departure time interval due to the shift. This graph illustrates the gains for passengers who wants to depart between 5:40 and 6:30 because they have access to a more suitable train thanks to the shift. However, this graph also shows the important loss for passengers who want to depart between 6:30 and 8:50 because the shifted train departs earlier than before for them. When summing the areas under the curves, the final statement show a net loss for passengers with a total consumer surplus of -265 SEK. This loss is caused by the higher number of passengers who wants to depart around 7:10 in comparison with a departure around 6:40.

Concerning the producer surplus, we present in Figure 4 the producer surplus change per path. This graph highlights the shift of the demand from the shifted train to the other trains departing right after the shifted train. The total producer surplus obtained is -51 SEK.

To conclude, the departure time shift caused a net total loss of welfare of -317 SEK. This illustrates that shifting this train is not a good allocation of rail resources for this OD. Therefore, unless there is a strong need to favour passengers willing to depart between 5:40 and 6:30, we do not recommend implementing this shift.

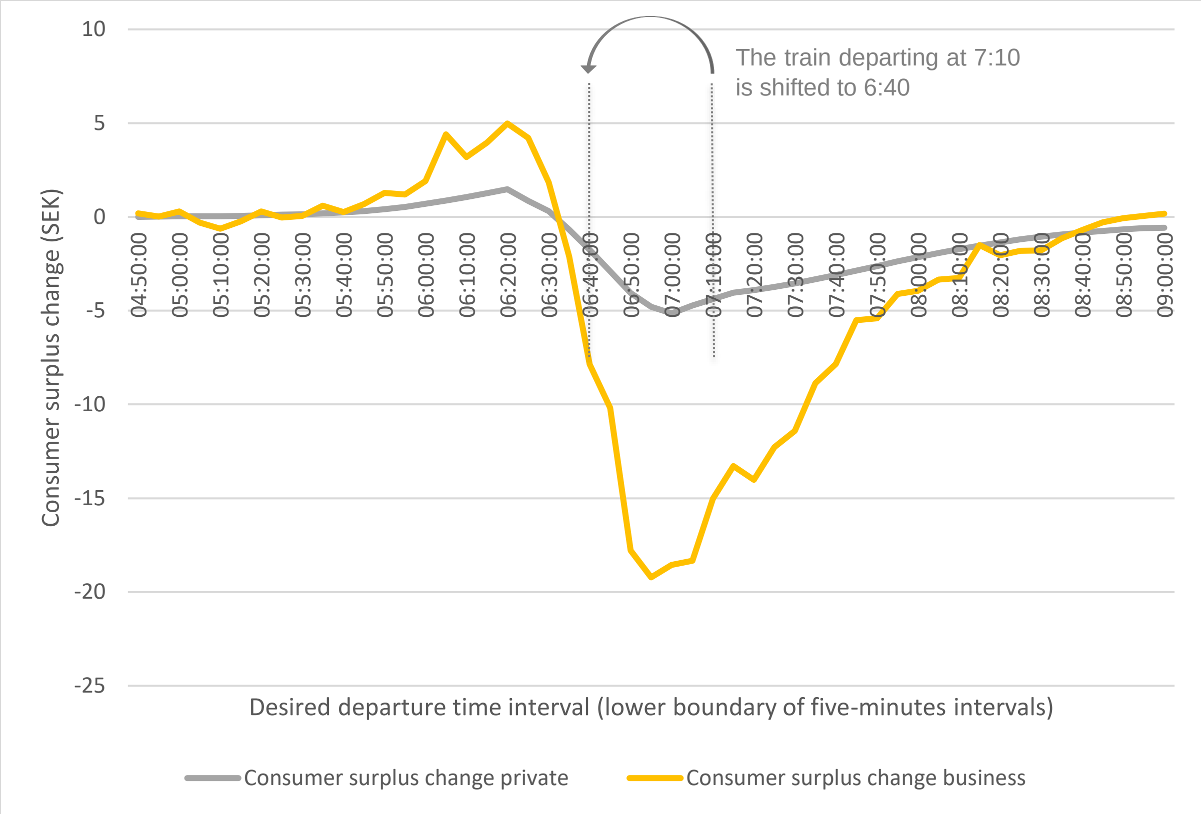

Figure 3: Consumer surplus change per demand segment and per desired departure time interval

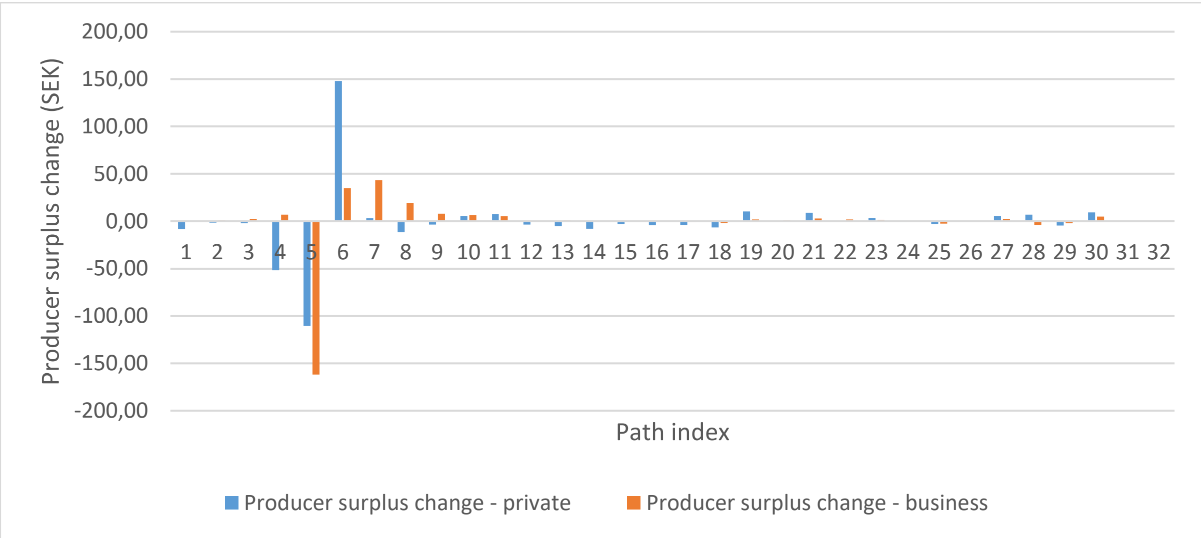

Figure 4: Producer surplus change per path. The path number five corresponds to the shifted train

4. Discussion and conclusion

In this paper, we present a method that allows rail planners comparing timetables with different departure times in order to optimise the rail supply for interregional passengers. This method is an improvement of the previous methods proposed in the literature because it accounts for an elastic passenger demand in the welfare calculations. Our method can be used to improve timetables not only in state-owned monopoly situations, but also to better solve conflicts between operators for capacity allocation in open rail markets.

However, some limitations exist. Indeed, in our situation, the welfare calculations rely on the validity of schedule-based models. This means that the limitations of schedule-based models, e.g. linear valuations, reduce the validity of our approach. In addition, the implementation of our method requires an important amount of work and data, e.g. the desired departure time distribution(s), a detailed network description, and the estimation of the total rail demand. Future research should therefore aim at simplifying the implementation of this method to spread its usage.

Moreover, our assumption that the production costs and fares of each train are not affected by departure time shifts is not valid for large shifts (say more than 30 minutes) or when trains are added or removed. However, such limitation is minor because substantial modifications are rare at the timetabling stage. Indeed, the number of trains and the approximate frequency of each line is usually decided in the line planning stage occurring before the timetabling stage.

To conclude, we improved the current literature on the welfare assessment of timetables by presenting a method that enables to compare the welfare of several timetables having different departure and arrival times. This method has the asset to be applicable to any interregional timetable and to account for the welfare with an elastic demand instead of an aggregated generalised cost for timetable comparison. However, our method requires an important amount of work and data to be implemented. Future research should be directed towards solving these limitations.

References

Ali, A.A., Warg, J., Eliasson, J., 2020. Pricing Commercial Train Path Requests based on Societal Costs. Transp. Res. Part A 132, 452–464. https://doi.org/10.1016/j.tra.2019.12.005

Broman, E., Eliasson, J., 2019. Welfare effects of open access competition on railway markets. Transp. Res. Part A 129, 72–91. https://doi.org/10.1016/j.tra.2019.07.005

Cascetta, E., Coppola, P., 2012. An elastic demand schedule-based multimodal assignment model for the simulation of high speed rail (HSR) systems. EURO J. Transp. Logist. 1, 3–27. https://doi.org/10.1007/s13676-012-0002-0

Douglas, G.W., Miller, J.C.I., 1974. Quality Competition, Industry Equilibrium, and Efficiency in the Price Constrained Airline Market. Am. Econ. Rev. 64, 657–669.

Lundqvist, L., Mattsson, L.-G., 2001. National Transport Models - Recent Developments and Prospects. Springer US. https://doi.org/10.1007/978-3-662-04853-5

Parbo, J., Nielsen, O.A., Prato, C.G., 2016. Passenger Perspectives in Railway Timetabling: A Literature Review. Transp. Rev. 36, 500–526. https://doi.org/10.1080/01441647.2015.1113574

PTV, 2020. PTV Visum 2020 Manual.

Quinet, E., Vickerman, R., 2005. User surplus, in: Principles of Transport Economics. Edward Elgar Publishing, Inc., Cheltenham, pp. 222–223.

Robenek, T., Azadeh, S.S., Maknoon, Y., de Lapparent, M., Bierlaire, M., 2018. Train timetable design under elastic passenger demand. Transp. Res. Part B Methodol. 111, 19–38. https://doi.org/10.1016/j.trb.2018.03.002

Robenek, T., Maknoon, Y., Azadeh, S.S., Chen, J., Bierlaire, M., 2016. Passenger centric train timetabling problem. Transp. Res. Part B Methodol. https://doi.org/10.1016/j.trb.2016.04.003

Svedberg, V., Aronsson, M., Joborn, M., 2017. Railway Timetabling Based on Cost-Benefit Analysis. Transp. Res. Procedia 22, 345–354. https://doi.org/10.1016/j.trpro.2017.03.041

Trafikverket, 2018. Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 6.1.

Vautard, F., Liu, C., Fröidh, O., Byström, C., 2019. Estimation of interregional rail passengers valuations for their desired departure times. Submitt. to Transp. Res. Part A.

Wilson, N.H.M., Nuzzolo, A. (Eds.), 2009. Schedule-Based Modeling of Transportation Networks, 1st ed. Springer US. https://doi.org/10.1007/978-0-387-84812-9