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The impact of route guidance, departure time advice and alternative routes on door-to-door travel time reliability: Two data-driven assessment methods

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ABSTRACT
Conventional travel time reliability assessment has evolved from road segments to the route level. However, a connection between origin and destination usually consists of multiple routes, thereby providing the option to choose. Having alternatives can compensate for the deterioration of a single route; therefore, this study assesses the reliability and quality of the aggregate of the route set of an origin-destination (OD) pair. This paper proposes two aggregation methods for analyzing the reliability of travel times on the OD level: 1) an adapted Logsum method and 2) a route choice model. The first method analyzes reliability from a network perspective and the second method is based on the reliability as perceived by a traveler choosing his route from the available alternatives. A case study using detailed data on actual travel times illustrates both methods and shows the impact of having variable departure times and the impact of information strategies on travel time reliability.

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Introduction

The robustness of road networks and the reliability of travel times are of great importance, as a large share of trips is taken up by road and the prospect of suffering unexpected delays and unreliable travel times on the network is undesirable. Current literature about the assessment of reliability mainly focuses on the link or route level (Lomax, Schrank, Turner, & Margiotta, 2003; Van Lint, Van Zuylen, & Tu, 2008). This implies that the travel time reliability of separate routes can be determined, but there is no method yet, as far as the authors are aware, to analytically assess the reliability and quality of the aggregate of all the routes between two locations. Having such a method is important as having alternative(s) can compensate for the deterioration of a single route. Furthermore, it is unknown how the perception of reliability of the aggregate of available routes depends on the travel behavior of the user.

This paper presents a data-driven approach that can be used to evaluate the reliability of travel time from door to door (origin-destination (OD) connection level) by considering multiple-route and departure time alternatives. The results of the method can be used to make an assessment of the current network performance and to get an indication of how much the reliability of the travel time on OD relations can be improved by giving departure time and route choice advice and by improving the availability and quality of route alternatives. Compared to the assessment of reliability of travel times on a route or road segment level, the assessment of an OD level might result in other, better informed, investment decisions for these types of measures.

The main question that is addressed in this paper is how multiple routes or departure times should be combined for an evaluation of the travel time reliability of the route set or departure time set.

The next sections present the route aggregation methodology, results from a case study in the region of Amsterdam and conclusions and recommendations.

Route aggregation methodology

Route aggregation can be done from network and user perspectives. The network perspective considers all relevant route alternatives at the same time. The user perspective depends on the route choice of the travelers and the level of information that they have. The following subsections present the model framework that we use in this article to aggregate routes from a network and user perspective, the methodology to aggregate routes from a

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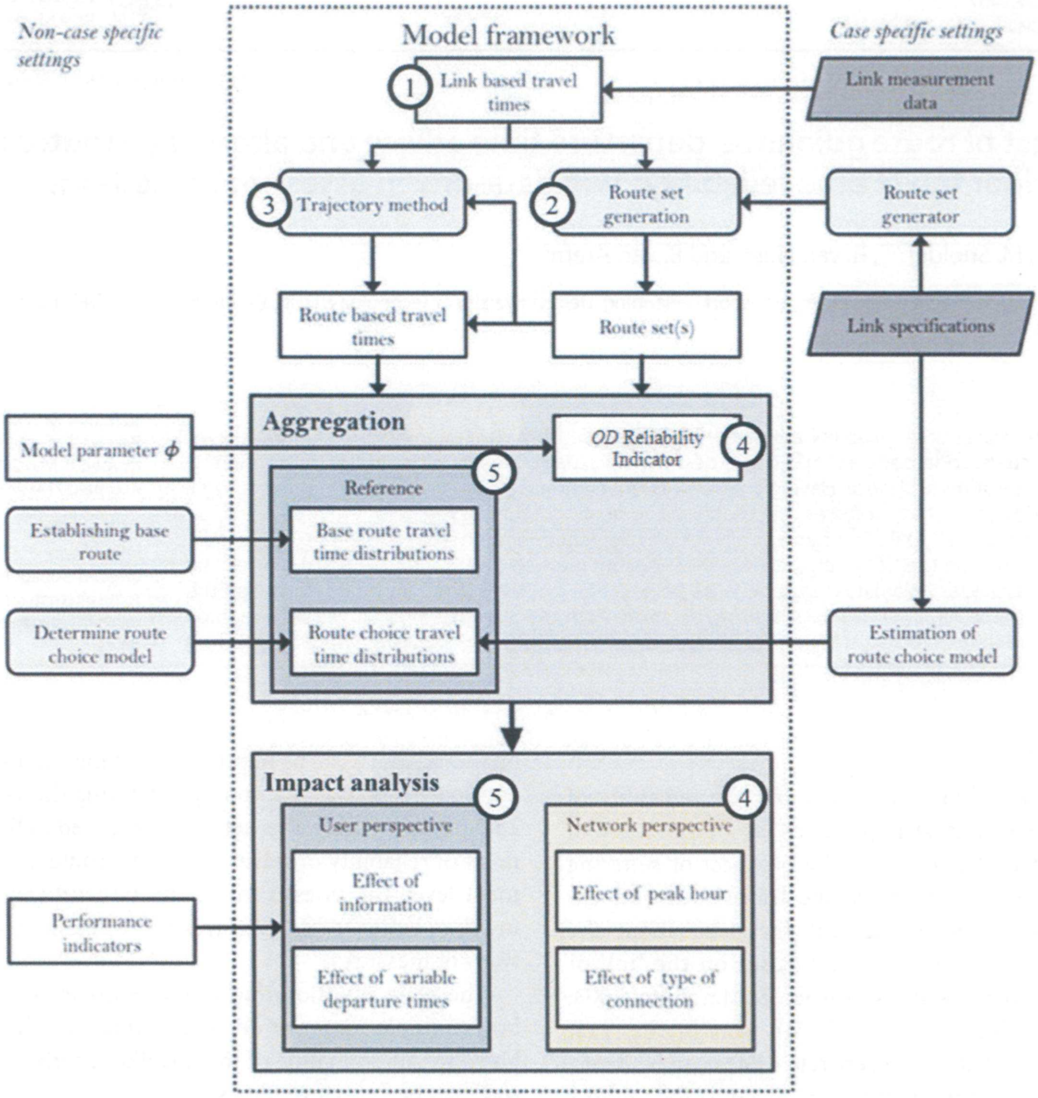


Figure 1. Model framework.

network perspective, and the methodology to aggregate routes from a user perspective.

Model design

Figure 1 shows the model framework that is used to compute the OD reliability from a network perspective and the perceived reliability from a user perspective. Depending on the definition of reliability, reliability may focus on non-recurrent and/or recurrent events. The proposed framework can deal with both types of events. In the case study peak and off-peak periods are distinguished in order to account for expected variations between these periods. Similarly, the framework can be used for within- and between-day travel time reliabilities.

The algorithmic approach of the model framework is enumerated below (the numbers below refer to the numbers in the figure):

1. Link-based travel times: the method is based on link-based travel times which include delays at intersections. Aggregation of link travel times leads to route travel times. If travel times on the route level are a priori present, this step and steps 2 and 3 are unnecessary.
2. Route set generation: route sets are generated per observation (multiple times during a day) in order to take the changes under traffic conditions over time into account. The following subsection explains how the routes are generated.
3. Trajectory method: the trajectory method (assuming a movement over time and thereby using measured link travel times corresponding with that movement over the route) is used to compute the actual route travel times based on link travel times.

4. OD reliability indicator: the OD reliability indicator aggregates routes from a network perspective. This indicator is computed based on the route set and route travel times. The OD reliability indicator is computed for the peak and off-peak periods and for different types of OD relations (urban or highway) in order to determine the impact of time of day and type of connection on connection quality. The following subsection explains this indicator in more detail and the section about the case study describes the results for the peak and off-peak periods and for different types of OD relations for a case study.
5. Perceived reliability: determination of how the availability of route alternatives and level of information influences the perceived connection reliability. Reference distributions are established (base route) which are compared with a distribution corresponding to a fully informed user and a distribution following from a case-specific route choice model. Furthermore, the effect of variable departure times is investigated. Subsection "User Perspective" explains this indicator in more detail and the section about the case study describes the impact of information and variable departure times for a case study.

Network perspective

The travel time reliability on a connection (OD) level from a network perspective is referred to as the OD reliability. In order to determine an indicator for OD reliability, the aggregation of routes to a single representative value is necessary. In this subsection, an indicator for OD reliability is assembled based on conventional aggregation techniques.

We can establish a set of criteria where the indicator must comply with:

1. *Number of alternatives*. The indicator must take the number of available alternatives into account. More alternatives should have a positive effect on the outcome of the indicator.
2. *Dispersion*. Increased dispersion of travel times of the route set should have a negative effect on the outcome of the indicator (ceteris paribus).
3. *Stability*. The indicator must be stable. As the number of alternatives increases, the effect measured must be less. The difference for examples 30 and 31 alternatives is negligible, which must be represented in the outcome. For the dispersion of travel times, increase should always have an increasing negative effect on the outcome, although this effect must not diverge unrealistically.
4. *Freeflow reference*. The indicator should not only take the dispersion of travel time into consideration, but also the actual delay compared to the reference value.
5. *Not case specific*. The indicator and involved parameters are preferably not case specific, thereby being more representative for alternative cases.

Two conventional aggregation methods can be identified. The first method is the scaling of the route travel times using a type of weight attribute. This results in a weighted or scaled mean travel time distribution on the OD level. A disadvantage of this method is that the method finds an aggregated travel time that is always higher than the minimum travel time of the two routes and therewith does not show the benefits of having multiple-route options. Another method is a derivative of a route choice model where instead of a weighted mean, the aggregate quality can be determined using the logarithm of the divisor of the logit model. We refer to this second method as the "Logsum" method (Ben-Akiva & Lerman, 1985; Train, 2003).

The Logsum method is a measure of consumer surplus in the context of logit choice modeling (De Jong, Daly, Pieters, & Van der Hoorn, 2005). The scaling is based on the exponent of the route travel times, instead of scaling by probability. The Logsum method uses log of the denominator of a logit route choice model as the aggregate quality indicator and corrects for the exponents with a logarithm. The Logsum calculation method is shown in Eq. 1. We assume $\tau_{i,t}$ to be the travel time on route i in route set R for an observation time t. Also note that the inverse of parameter ϕ corrects for the ϕ parameter of the applied logit model.

$$\tau^{LS}_{agg,t} = \frac{1}{\phi}\ln\left[\sum_{i\in R}\exp\left(\phi * \tau_{i,t}\right)\right] \quad (1)$$

The Logsum method, to the contrary of the scaled mean method, gives an estimation of the minimum travel time. As the travel time of routes which is higher than the minimum route travel time increases, their respective share in the aggregate travel time decreases. In Figure 1, the representation of the Logsum is illustrated, along with the scaled mean method and the minimum route travel time for an exemplary connection consisting of two routes. The aggregation is based on all routes, instead of just the minimum travel time and still simulates an aggregate travel time close to the minimum route travel time. Figure 2 shows that when the travel times of both routes are (close to) equal, the indicator presents a value below the minimum travel time. When the number of equal travel time alternatives increases, the aggregate

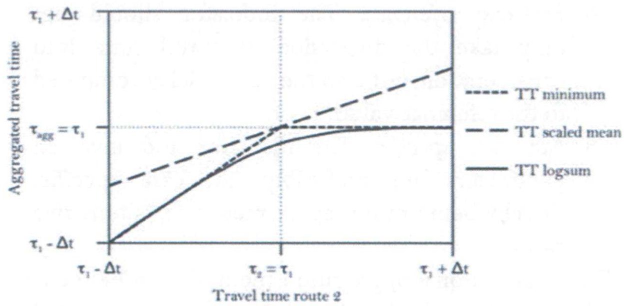


Figure 2. Example illustration of scaled mean and Logsum aggregation methods.

value decreases, thereby assigning a "bonus" for having multiple alternatives.

Indicator based on travel time

This part elaborates on the analytic indicator to assign a value to the OD reliability of a connection, thereby considering the conventional methods as described in the subsection before. As described earlier, the scaled mean method is inherently inappropriate for an analytic aggregation of routes. The Logsum is more appropriate since it shows improvement in the aggregated results when more alternatives are considered and it is possible to implement the method with different types of input (e.g., travel times, relative travel times, utility values, etc.). Although this indicator is theoretically justified and overall shows behavior in line with the criteria, the basic formulation of the Logsum method shows significant disadvantages. The first disadvantage is that the basic formulation of the method shows an absolute dependence on the number of alternatives, which is independent of the travel times. The second disadvantage is that for lower travel times, the influence of having more alternatives is larger than that for higher travel times. This size dependence can be considered counterintuitive, as for longer travel times and thus usually longer distances, a larger network density can be expected with more alternatives. The third disadvantage is that the Logsum might become negative when the travel times are too low.

In order to compensate appropriately for this dependency, redefinition of the basic formulation is necessary. Based on Ben-Akiva and Lerman (1985), a first redefinition of the basic formulation of the Logsum method for travel time is described in Eq. 2:

$$\tau_{agg,t}^{LS} = \overline{\tau_t} + \frac{1}{\phi}\ln\left[\frac{\sum_{i\in R}\exp(\phi * (\tau_{i,t} - \overline{\tau_t}))}{n}\right] + \frac{1}{\phi}\ln(n) \tag{2}$$

where $\overline{\tau_t}$ is the average travel time over all routes i for observation time t. The Logsum method has been redefined into three parts: (1) an average travel time, (2) a part that aggregates the variable parts with respect to the average value and (3) a constant value. This redefinition shows that as the average travel time increases, the size of the route set becomes less influential, regardless of the differences in travel times between routes. This would mean that longer connections are valued differently than shorter connections. To compensate for this, the dispersion with respect to the mean is not considered, but the dispersion of the delay, or in other words, the difference between the measured travel times on the routes and the freeflow travel time of the fastest freeflow route τ_{ff}, is considered. From here, we can redefine Eq. 2 as depicted in Eq. 3

$$\tau_{agg,t}^{LS} = \Delta\overline{\tau_t} + \frac{1}{\phi}\ln\left[\frac{\sum_{i\in R}\exp(\phi * (\tau_{i,t} - \tau_{ff} - \Delta\overline{\tau_t}))}{n}\right] + \frac{1}{\phi}\ln(n) + \tau_{ff} \tag{3}$$

where $\Delta\tau_t$ is the mean of the differences $\tau_{i,t} - \tau_{ff}$. From here, the basic formulation of the Logsum can be adapted, which is depicted in Eq. 4:

$$\tau_{agg,t}^{LS} = \frac{1}{\phi}\ln\left[\sum_{i\in R}\exp(\phi * (\tau_{i,t} - \tau_{ff}))\right] + \tau_{ff} \tag{4}$$

Note that the aggregation is now based on the difference between the route travel time and the freeflow time of the fastest freeflow route. This way, comparability over all observations $t \in T$ is ensured, as size dependency of the travel time input is now the same despite the length of the route. The addition of the constant has no influence on the behavior of the indicator and it therefore remains theoretically justified.

The final addition which is necessary is the compensation for the fact that the distance and travel time between OD pairs can be significantly different and the value of the Logsum is dependent on this. Therefore, it is better to use a relative measure that compensates for this difference. In this case, this perspective can be added by, once again, including the freeflow travel time of the fastest freeflow route as depicted in Eq. 5, thereby completing the OD reliability indicator I_{conn}. Note that this value is still per observation $t \in T$ and that this addition does not influence the stability or behavior of the method. Equation 5 is used in the remainder of this paper as an indicator for OD reliability (network perspective).

$$I_t^{conn} = \frac{1}{(\phi * \tau_{ff})}\ln\left[\sum_{i\in R}\exp(\phi * (\tau_{i,t} - \tau_{ff}))\right] + 1 \tag{5}$$

As the value of the indicator goes up, the lower is the score for the quality of the OD pair. With regard to the redefined Logsum indicator, we can conclude the following:

1. The indicator is balanced. It is not overly sensitive to either the number of alternatives or the dispersion of travel time.
2. The method remains stable when the delays and number of alternatives increase. The addition of the fastest freeflow travel time does not alter the behavior of the indicator. However, the method is not bounded and will become unstable when the value tends to ∞ or $-\infty$. For practical purposes, this is of no consequence as practical input is bounded. For realistic values, the outcome value remains positive.
3. As the differences in travel time compared to the freeflow time of the fastest freeflow route increase, the value of the indicator increases as well.
4. As the number of alternatives increases, the derivative of the indicator becomes gradually less. This is in accordance with the expectation that at some point, the effect of having multiple alternatives becomes negligible. The degree of this mitigation over n is dependent on the model parameter ϕ.
5. As the delay or the travel time dispersion increases, the value of the indicator shows an almost linear increase. This is in accordance with the fact that the negative effect of delay does not mitigate as it increases. More dispersion should always negatively impact the outcome.
6. Note that every route, despite its characteristics, is valued as mutually equal (there is no distinction in importance).
7. Note that the indicator is computed for each time step separately. It is possible to compute other indicators for travel time reliability (e.g., indicators specified in the next subsection) for an interval T based on the aggregated route travel times with the adapted Logsum method.

Finally, a logit model assumes independent and identically distributed unobserved or error terms in the utility function with the same variance. Since a route overlap is possible, these assumptions might not be valid in all cases. A route overlap factor could be introduced. However, such an overlap factor does not account for the location where disturbances occur and the possibility of switching routes en route (which requires overlap). Because the possibility of switching routes is important for the reliability of travel times on an OD level, an overlap factor is not introduced in the network indicator for reliability.

Model parameter φ

The model parameter ϕ in Eq. 5 represents travelers' appreciation of additional alternatives in the choice set given the travel times on these routes. Ideally, this parameter should be estimated from data. However, the estimation of this parameter is outside the scope of this paper. In this paper, ϕ is set to -1. This provides a representative balance of influence between the number of alternatives and the route travel time dispersion over the routes.

Route set generation

In order to compute the OD reliability indicator (Eq. 5), a route set is required. For the purpose of the research performed in this paper, a route set generator with the following specifications is used:

1. The algorithm is Dijkstra-based (Dijkstra, 1959).
2. The algorithm employs Labeling (Ben-Akiva, Bergman, & Daly, 1984) to determine the fastest route, the shortest route and the highest comfort route (highest proportion of highway). These determined routes are deterministic.
3. A derived form of the K-shortest path method is used (original methodology by Yen (1971)). Link elimination is performed a single time on the fastest route at the link around 50% of the routes' distance.
4. After determining deterministic routes, links are subjected to a stochastic influence that slightly alters the measured travel time (Monte Carlo approach). After this "adjustment," the algorithm determines whether an additional route has become feasible in comparison to already found routes. If so, it is added to the route set. This is done for a number of x simulations. Duplicate routes are eliminated. The type of links subjected by this stochastic influence can be manually adjusted based on the freeflow speed. A manually adjusted model parameter determines the threshold to what links a stochastic influence is assigned. Links with freeflow speeds below the threshold are thereby not stochastically influenced.

The selection is based on evaluations performed by Bekhor, Ben-Akiva, and Ramming (2006). The validity of the method (e.g., coverage, use of motorways, overlap, no U-turns, etc.) is manually tested for different types of OD relations.

This route set generation is performed at every observation t in T. Since the route set generation depends on the travel times in the network which vary over time, multiple, variable route sets for a single OD pair are acquired. As the route set is aggregated at every observation t, this variability is considered desirable as it increases the chance of a representative coverage.

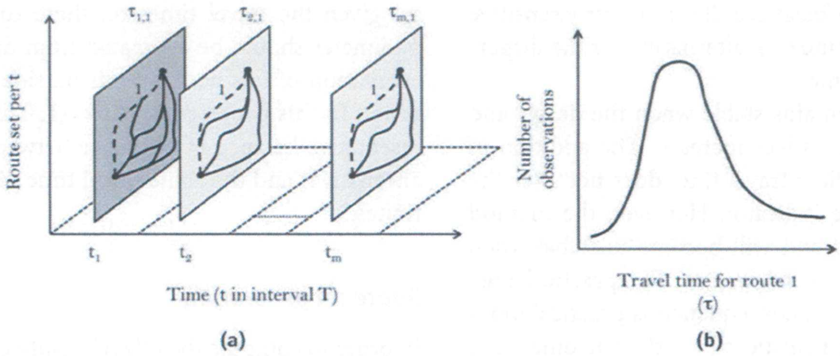


Figure 3. Example of route sets and single route travel time distribution. (a) Route sets and travel time selection for rote 1. (b) Travel time distribution for route 1.

User perspective

The quality and reliability of a connection from a user perspective are largely dependent on the choices of the traveler and the travel time distribution observed/experienced given those choices. In order to determine the perceived connection reliability from a user perspective, we observe a virtual traveler in a predetermined interval T. Note that T can refer to different departure times on one day which refers to within-day travel time reliability. T can also contain observations for the same departure time over multiple days which refers to day-to-day travel time reliability.

Within the predetermined interval T, we select a number of m observations for which we determine the route(s) the traveler would take in case he would depart at time t. When the OD reliability indicator aggregates the routes per observation t, we now observe a single route per observation t and the corresponding travel time $\tau_{i,t}$. Depending on the type of user, the route chosen at time t alters. Note that the route set does not necessarily remain the same at every observation t (see previous section).

If we want to determine, for example, the travel time distribution $[\tau_{1,1}, \tau_{2,1}, \ldots, \tau_{m,1}]$ for a traveler that always uses route 1, then we have to determine the travel time on route 1 at every observation t in the predetermined interval T. This is illustrated in Figure 3a and b. The example presented is in fact a route travel time distribution as a single route i is observed, while at the same time it represents a user who always takes a single route for his trip.

Figure 4 shows an example in which the user selects different routes in different time intervals (dotted lines). Therefore, the perceived travel reliability depends on the route choice of the user. As this type of aggregation of routes still leads to a travel time distribution, the travel time reliability can be determined using (conventional) distribution-based performance indicators as described later in this section.

Base route travel time distribution

The base route is the route in the route set of the connection representing a version of the connection when only a single route is available. To prevent bias and to provide a minimal baseline, the base route is the fastest freeflow route in the route set. For this route, a travel time distribution can be computed for interval T.

Route choice model

The route set is generated in the same way as explained in the previous subsection. In this case, a route overlap is considered because the pre-trip route choice is assumed for the route choice model. Also, since the algorithm is

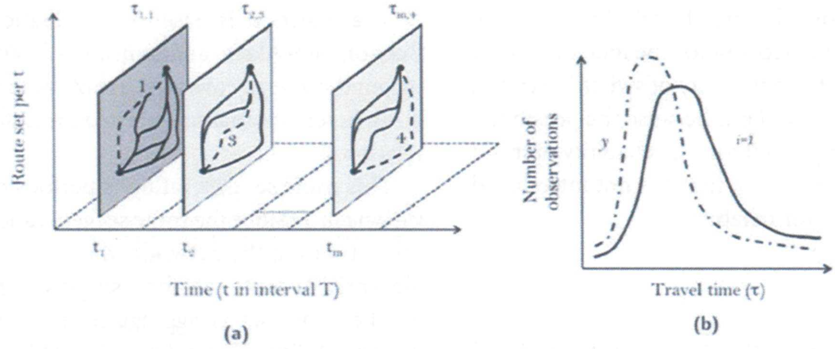


Figure 4. Example of route sets and travel time distribution of a combination of routes. (a) Route sets and travel time selection for traveler y. (b) Travel time distribution for route 1 and traveler y.

applied per observation, the route choice model must be concise and must not require long computation times. We apply a logit model incorporating the median route travel time, the difference between the 90% percentile and the median per route and the highway proportion of the route. As two routes, which differ only by a slight percentage of the total distance, cannot be considered equally different to two non-overlapping routes, it is preferable to use a model that incorporates this fact, without being overly complicated. Based on the discussion on model practicality and accuracy by Bierlaire (2008), the path size logit is chosen to account for the overlap of routes. Equation 6 shows the utility function of the path size logit model.

$$U_p = \beta_{PS}\ \ln\left(PS_p\right) + \beta_{med}\tau_{med,p} + \beta_{per90}\tau_{90\%-50\%,p} + \beta_{HW}\varphi_{HW,p} + \beta_{urb}(1-\varphi_{HW,p}) \quad (6)$$

$$PS_p = \sum_{a\in\Gamma_p} \frac{L_a}{L_p}\frac{1}{\sum_p \delta_{a,p}};\quad \{\delta_{a,p} = 1\ if\ a\ \in p,\ 0\ \text{otherwise}\} \quad (7)$$

where p refers to path, Ln(PS) is the logarithm of the PS factor as explained in more detail in Eq. 7, $\tau_{med,p}$ is the median travel time for path p, $\tau_{90\%-50\%,p}$ is the 90% minus the 50% travel time for path p (indicator for reliability), and $\varphi_{HW,p}$ is the highway proportion of path p. L_a is the length of link a, L_p is the length of path p and Γ_p is the set of links of path p.

The formulation and estimation of the parameters (β) of the components are based on the studies byRamming (2002), Ben-Akiva and Bierlaire (1999), Lam and Small (2001), Bekhor et al. (2006) and Bierlaire, Frejinger, and Stojanovic (2006). Since these studies consider different components, expert judgment was used to set the parameters: $\beta_{PS} = 1$, $\beta_{med} = -0.37$, $\beta_{Per90} = 1.77\ \beta_{med}$, $\beta_{HW} = -2.2$ and $\beta_{UR} = -4.4$.

Selected travel time performance indicators

Many different indicators can be used for the reliability of travel time, since there is not a single indicator that outperforms the others. Based on Pu (2011) and Wesseling (2013), the following set of criteria are used to select appropriate indicators:

1. Simple and concise method: A simple measure with a concise and clear value is preferable over a complex method.
2. Increasing disutility as delays grow longer: The measure incorporates the length of the delay and assigns a proportionate value when delay increases, but takes skewness of the distribution into account.
3. Median-based instead of mean-based: The measure uses the median as it is less sensitive to outliers in the data.
4. No arbitrary parameters: The measure is not, or in a limited way, dependent on arbitrarily chosen parameters.
5. Well known, expressive and easily communicable: The measure must present a value that is easily understood and communicated.
6. Can be converted into a monetary value: Although not relevant for this paper, in future research assigning a monetary value might prove necessary.

Since no single indicator complies with all the criteria, prioritizing the criteria is necessary. The Buffer index (median) complies with most of the criteria and is therefore selected. The indicator is computed on the OD level for interval T. This implies that $\tau_{90\%}$ and med are, respectively, the 90% and 50% percentiles of the travel times on the routes chosen by the traveler for every observation t in T. The definition is as follows:

$$BI_{OD,T} = \frac{\tau_{90\%,OD,T} - med_{OD,T}}{med_{OD,T}} \quad (8)$$

Reliability gains often have to be converted into monetary units. The value of reliability is often used for this. Since the value of reliability is related to the standard deviation, the standard deviation is selected as well. It must be noted that this indicator does not incorporate skewness. In this equation, $\tau_{OD,t}$ is the travel time on the route chosen by the traveler at observation t. $\mu_{OD,T}$ is the mean travel time in interval T over all the routes chosen in interval T.

$$\sigma_{OD,T} = \sqrt{\frac{1}{m-1}\sum_{t\in T}\left(\tau_{OD,t} - \mu_{OD,T}\right)^2} \quad (9)$$

An indicator is added that has the main focus on the size and width of the peak of the distribution. For this purpose, the Mean Absolute Deviation (MAD) about the median is selected (El Amir, 2012). This indicator is proportionate and median-based and has no arbitrary parameters.

$$MAD_{OD,T} = \frac{1}{m}\sum_{t\in T}\left|\tau_{OD,t} - med_{OD,T}\right| \quad (10)$$

Finally, an indicator that specifically indicates delay suffered is determined. In this case, the time lost per connection is of interest. This indicator is the absolute delay measured per observation in the distribution scaled to the freeflow travel time of the base route.

$$\tau^{loss}_{OD,T} = \sum_{t\in T}\left|\tau_{OD,t} - \tau^{b}_{OD,ff}\right| \quad (11)$$

where $\tau^{loss}_{OD,T}$ is the aggregate delay for the total number of observations T, $\tau^{b}_{OD,ff}$ is the base route freeflow travel time and $\tau_{OD,t}$ is a measurement at observation t for a specific travel time distribution.

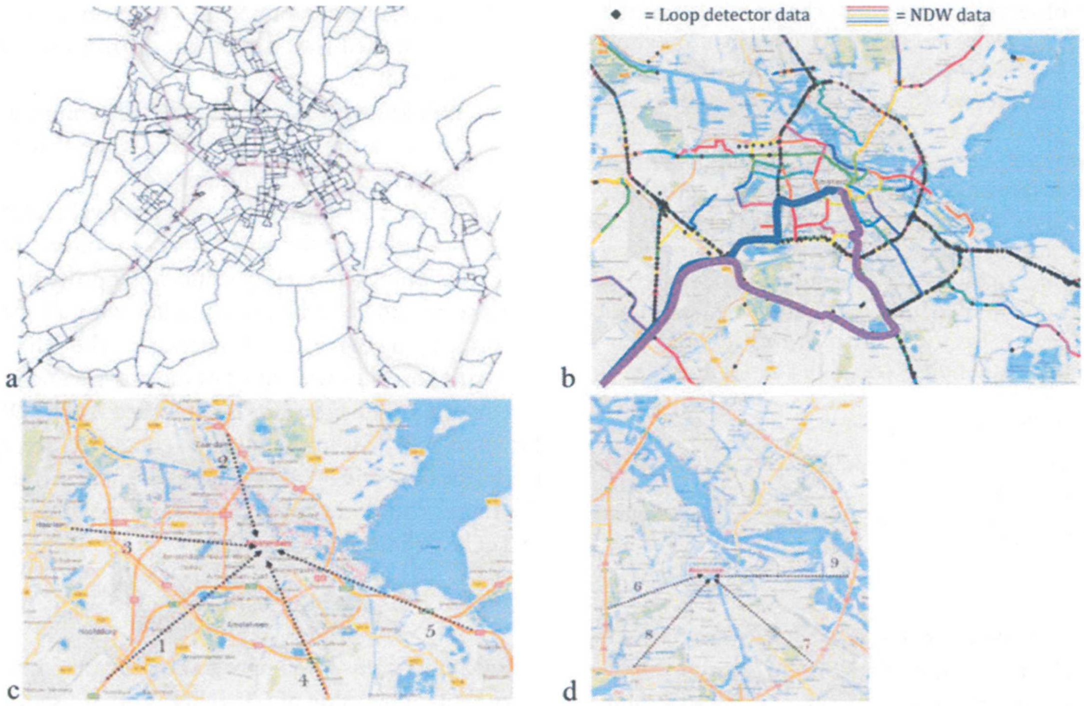


Figure 5. Case study network: (a) model network impression, (b) data availability, (c) highway OD pairs, and (d) urban OD pairs.

Case study: Amsterdam

Network specifications

In Figure 5a, the network that is used for the case study is presented. The network details are provided in Table 1. In this research, originally nine OD relations were used. Five of these relations are long distance relations which use the highways. The other relations only use urban roads. Figure 5c and d shows these relations. The data quality for OD 8 appeared to be insufficient. OD 8 is therefore excluded from further analysis.

Data specifications

Data are derived from the Dutch National Data Warehouse for Traffic Information (NDW, 2014). This database comprises (real-time) travel times from the majority of the Dutch motorway network and important secondary roads from double induction loops, floating car data, camera system, etc. The data are linked to the model network, thereby making it possible to derive corresponding link data. Delays at intersections are included in the camera, Bluetooth and floating car data. These delays are assigned to the links in the model network. Data are divided into measurement intervals with a single representative value for measurements in that time interval. In this study, a 5-minute interval is used, meaning that all measurements made within that interval for a specific link are smoothed to an average representative value. If no data are present, the algorithm assumes freeflow travel times on the respective links. Figure 5b shows data availability for the case study network.

Table 1. Network properties.

Network element	Quantity
Highway (speed ≥ 70 km/hour)	20,304
Urban (speed < 70 km/hour)	25,623
Total number of links	45,927
Number of nodes	33,062

In this paper, we consider two main time scenarios: *Peak hours* and *non-peak hours*. Thereby, as peak hours are recurrent, we consider the effects of these recurrent events. The effects of non-recurrent events, such as accidents or bad weather, are not considered specifically and their effects are mitigated by considering multiple days and multiple travel time performance indicators that compensate for outliers. Table 2 summarizes the case study specifications.

Results of the OD reliability indicator

At every observation t, a trajectory is started, simulating a departure at that time in interval T and the corresponding connectivity value found by the indicator. For both time scenarios, the result is the course of the quality of the connection, set against the departure time of the

Table 2. Case-specific aspects of measuring.

Aspect	Value	Note
Number of days observed	43	Tuesdays, September 4, 2012–June 25, 2013
Step size of departure times	5 minutes	—
Time interval T per day	3 hours	Peak: 7 am–10 am, Non-peak: 12 pm–3 pm
Number of intervals t in T	24	First 2 hours of T divided by step size
Number of connections (OD)	8	Original 9, one left out because of data shortage
Route set generation	Per interval t	*K*-shortest path, Labeling, Stochastic travel times (Monte Carlo). Choice based on Bekhor et al. (2006).

trajectories. The averaged results over 43 observed days are presented in Figure 6. Each line represents one OD relation.

Differences between peak hour and non-peak hour

At 7:00 am, at the start of the peak hour, the quality of the connections is comparable with the value found outside the peak hour. This can be said for both highway and urban connections. When departing at 9:00 am, the indicator value shows significant increases in comparison with the value found at 7:00 am, while outside the peak hour, we do not observe this degradation of quality.

Considering all connections, an average quality degradation of around 14% is observed. Outside peak hours, the quality of the connections remains stable. This is in line with the expectation. It can be said that during this period, the quality of the connections is less dependent on the travel time dispersion and more on the availability of alternative routes. During this period, the demand does not recurrently exceed road capacity, thereby having little differences in travel time dispersion over the interval. During this time, it is assumed that the quality of the connections is optimal; thus, OD reliability is maximized. Here, the differences under freeflow conditions can be observed.

Differences between highway and urban connections

Highway connections show greater degradation in OD reliability in comparison to the urban connections in the peak hour interval. Outside the peak hour, the behavior of the OD reliability of the connections shows similar behavior. Furthermore, it can be said that the highway connection shows larger dispersion of degradation over the observed days, while the degradation increase of urban connections is relatively stable. When comparing the OD reliability of the connections mutually under normal circumstances (no peak hour), it can be said that the OD reliability shows no obvious relation to the type of connection as both highways have varying scores. It can be said, however, that the OD reliability values of the highway connections are less spread out than the values of the urban connections, where the scores differ significantly. Based on these results, it can be said that the OD reliability of highway connection is less stable and more sensitive to degradation. However, it should be noted that the coverage of data on the lower network levels, and thus on the urban connections, is less than that on higher network levels such as highways. The fact that data gaps are compensated for with freeflow travel times may also be the cause of the higher stability of urban connections.

Results of the perceived connection reliability analysis

The results of the perceived connection reliability analysis can be distinguished as follows:

1. Analysis of the effect of having route information: This is done for a peak hour and non-peak hour scenario.

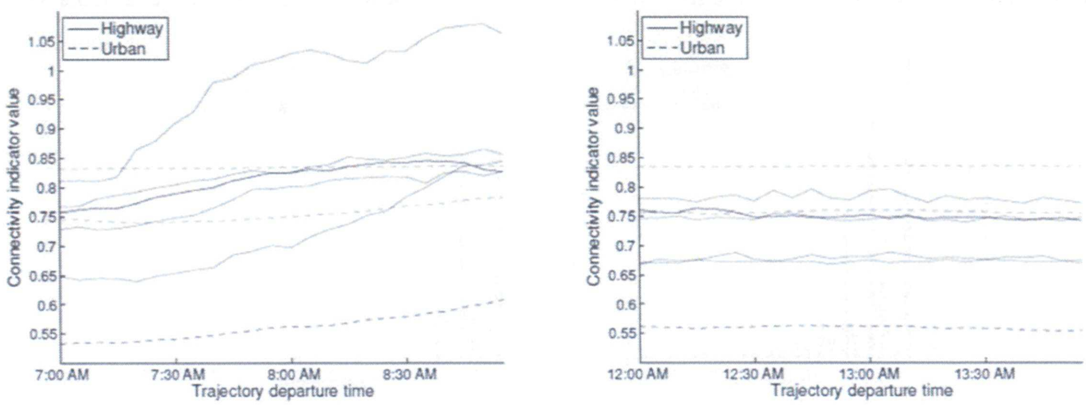


Figure 6. Averaged value of the OD reliability indicator set against departure time.

Table 3. Performance indicator values relative to the base route (indicator base route–indicator fastest path/route choice model/100%).

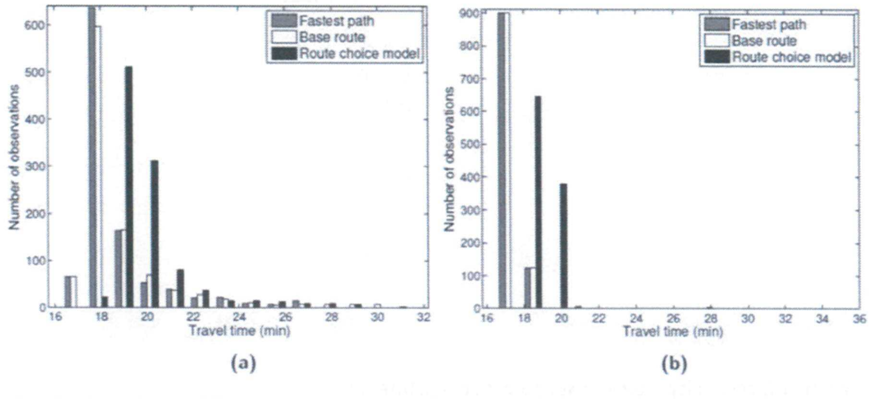
		OD 1	OD 2	OD 3	OD 4	OD 5	OD 6	OD 7	OD 9
Route choice model (%) 7:00–10:00 am	Average	− 6	− 3	+10	+1	+2	− 5	− 6	− 2
	Standard dev.	+23	+5	+79	+29	+39	+44	+62	− 13
	Buffer index	+40	+9	+74	+17	+43	+46	+63	− 29
	MAD	+2	− 3	+83	+47	+45	+44	+41	− 67
	Delay	− 61	− 18	+37	+69	+76	− 262	− 136	− 15
Fastest path (%)7:00–10:00 am	Average	+1	+1	+19	+7	+12	0	+1	0
	Standard dev.	+24	+5	+77	+39	+48	0	+29	− 1
	Buffer index	+19	+3	+64	+19	+39	0	0	0
	MAD	+22	+8	+82	+73	+46	0	0	0
	Delay	+14	+6	+69	+35	+37	0	+16	0
Route choice model (%) 12:00–15:00 pm	Average	− 8	− 6	+13	− 1	− 3	− 5	− 6	− 8
	Standard dev.	+26	+17	+74	+60	+57	+44	+60	− 8
	Buffer index	− 13	+454	+70	+67	+57	+47	+67	− 8
	MAD	+2	+16	+70	+62	+56	+44	+60	− 14
	Delay	− 207	− 18	+51	− 8	− 18	− 232	− 138	− 72
Fastest path (%)12:00–15:00 pm	Average	0	0	+18	+8	+4	0	0	0
	Standard dev.	+63	+10	+71	+62	+45	0	+20	0
	Buffer index	0	0	+72	+73	+58	0	+11	0
	MAD	+25	+7	+68	+73	+45	0	+11	0
	Delay	+7	+5	+70	+42	+30	0	+11	0

2. Analysis of the reliability gains of having a variable departure time within an interval: This is investigated for interval sizes of 15 and 25 minutes.

Effect of route information

For an evaluation of the perceived travel time reliability (user perspective), empirical reference travel time distributions for connections are acquired by simulating multiple trips for a fully informed (and compliant) user (fastest path) and a "normal" user familiar with the area (route choice model). These are compared with a simulated travel time distribution for an uninformed user (always taking the same route), who always takes the fastest route available (base route). As explained in the previous subsection, the travel time distribution for the average "normal" user is simulated with a path-size-logit-based route choice model that includes the reliability of route travel times in the utility function (Eq. 6). To assess the influence of route choice on the reliability of the travel times that a user experiences, it is assumed that the user makes the same trip at the same departure time on multiple days. The results are presented in Table 3. Note that positive relative values represent an improvement (e.g., higher average is a decrease in performance), while negative values represent a decline. Values are rounded to integers.

With regard to the base route, it is expected that because it is the fastest freeflow route, it should be the fastest outside peak hour. We distinguish the OD pairs where this is indeed the case (1,2,6,7,9) and the OD pairs where, despite this fact, the base route is rarely the fastest (3,4,5) due to regular delays on those routes. The route choice model shows occasional improvements with regard to travel time reliability, but has a persistent higher average and delay. This is in line with expectations as the route choice process is based on more properties than travel time. The fastest path algorithm represents a traveler that is fully informed about which routes are the fastest at a particular time. The results show a persistent improvement when compared to the reference distributions. With the exception of OD 6, where the base route is always the fastest as well, large improvements with regard



(a) (b)

Figure 7. Travel time distributions for an OD connection. (a) Travel time distributions, 7h00AM–10h00AM. (b) Travel time distributions, 12h00AM–15h00AM.

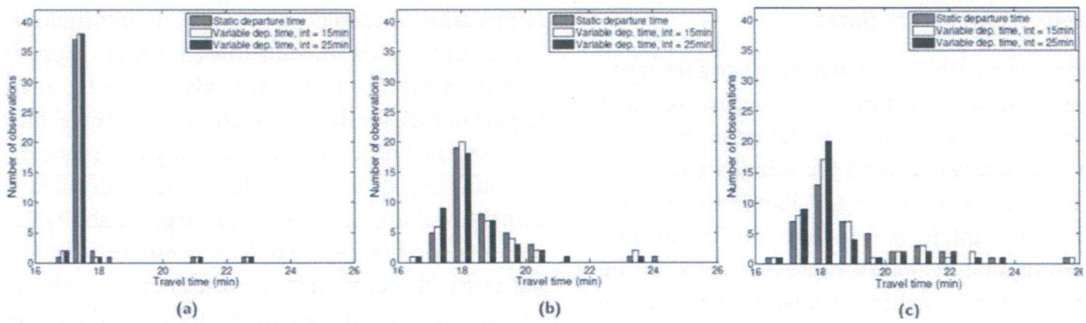


Figure 8. Travel time distributions for OD pair 1 for different departure times. (a) 7h00AM, (b) 8h00M and (C) 8h30AM.

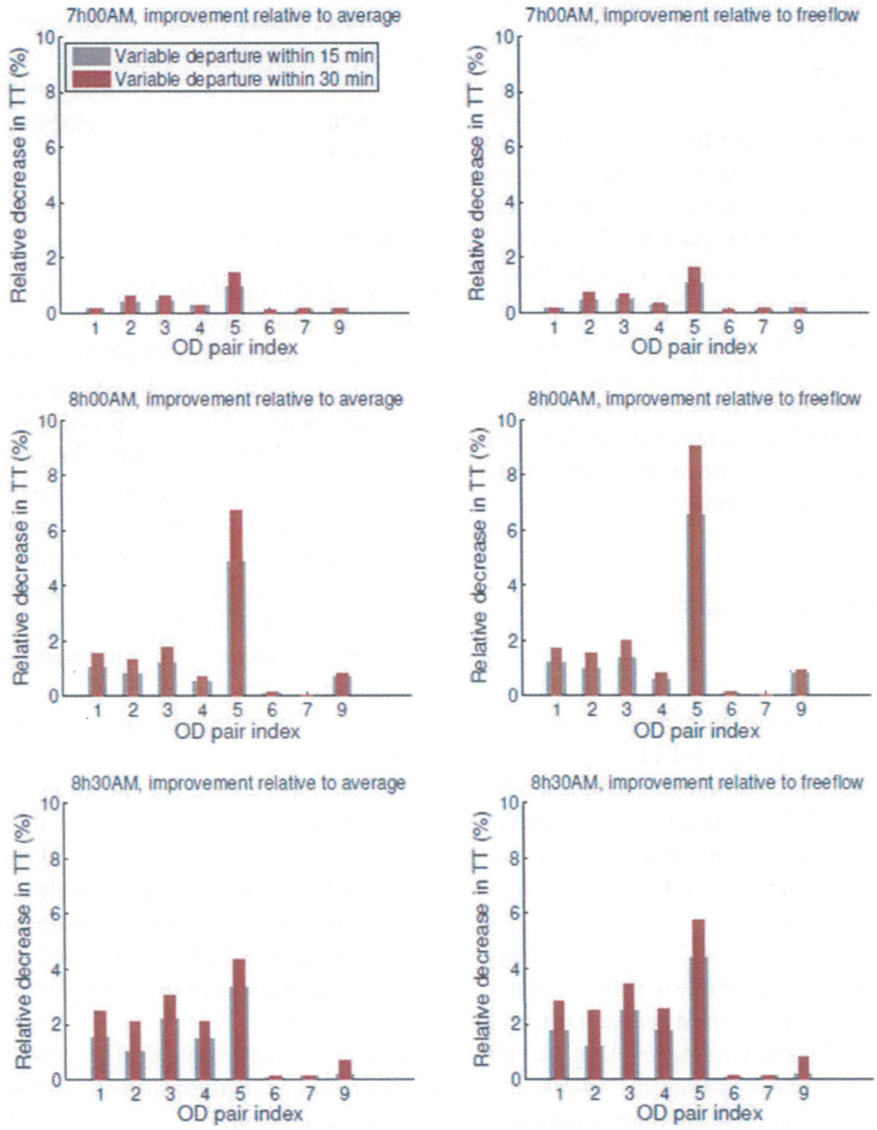


Figure 9. Relative decrease in delay with variable departure times, for 7:00 am, 8:00 am and 8:30 am (TT = travel time delay suffered).

to reliability and delay can be achieved when fully informing a traveler. Note that the improvement of the average is much smaller.

For illustrative purposes, the travel time distributions for a single OD (OD 1 of Figure 5c) are presented in Figure 7.

Effect of variable departure times

In this section, the possible gains of having variable departure times are described for three static departure times: 7:00 am, 8:00 am and 8:30 am. The departure times are varied within an interval around the initial static departure times. Interval lengths of 15 and 25 minutes are chosen by means of example. We assume a fully informed traveler, meaning that the fastest route is selected for the static departure times. Furthermore, we assume that the traveler is fully informed about the travel times within the interval around the static departure time, leading to the selection of the fastest route at the optimal departure time within the interval. For illustrative purposes, the results for OD 1 are shown in Figure 8.

Based on results of all OD pairs, we could determine that most indicators show a consistent improvement of the distribution for a variable departure time in comparison with a static departure time. This greatly differs between the OD pairs and ranges from 0% to 50%. Also, the improvements are most notable for highway-connected OD pairs and for the 30-minute interval. The improvements in average delay over the 43 days are presented in Figure 9, normalized by the average value of the static departure time distribution in the left column and normalized by the freeflow reference in the right column. The figure shows that even when assuming a fully informed user, significant improvements can be made.

Conclusion and recommendations

Conclusion

This paper introduced two aggregation methods for analyzing the reliability of travel times on the OD level: 1) an adapted Logsum method and 2) a route choice model. The first method analyzes reliability from a network perspective and the second method is based on the reliability as perceived by a traveler choosing his route from the available alternatives.

This paper showed that the adapted Logsum method is balanced in the sense that it is not overly sensitive to either the number of route alternatives or the dispersion of travel time. The case study for Amsterdam showed that the OD reliability indicator provides insight into the (degree of) degradation of connections as the peak hour progresses. The indicator can also be used to assess the reliability of travel times for different OD pairs which can, for instance, be used to compare project alternatives of new infrastructure projects.

The presented route-choice-model-based method can be used to analyze the perceived travel time reliability on the OD level with different information strategies: full information (and full compliance), no information (fixed route) and partial information ("normal" users familiar with the area). The method can also be used to analyze the impact of variable departure times on the travel time reliability on the OD level. The case study for Amsterdam and surroundings in the Netherlands, using detailed data on actual travel times, showed that large reliability improvements are possible when fully informing a user. Also, having a variable departure time within in the peak hour may improve travel time reliability, although the benefits are dependent on the degree of departure time flexibility.

Finally, it is possible to combine both methods. Instead of the route choice model, the adapted Logsum method can be used to aggregate route travel times for each time step separately. Based on these aggregated travel times, other indicators for travel time reliability (Eqs. 8–11) can be computed.

Recommendations

For the application of the OD reliability indicator, we recommend the following:

1. The value of the OD reliability indicator provides a good relative insight into connection quality, but the value itself is less expressive. It is recommended to determine a reference for what is a "bad" OD reliability value and what is "good."
2. The indicator does not account for overlap in routes. It is recommended to investigate the possibility of the inclusion of overlap and/or dominance in the OD reliability indicator in such a way that the possibility of en route switching can be taken into account.

For the user perspective, we recommend the following:

1. Estimation of the route choice model based on floating car data collected in the case study area, thereby providing a more realistic representation of the average "normal" traveler.
2. The fastest path advice assumes full compliance of the traveler. In reality, this will not be the case. It is recommended to investigate the compliance of travelers.

To improve methodological aspects of the framework, we recommend the following with respect to the data and route set generation:

1. The assumption of freeflow times on roads with data gaps leads inherently to underestimation. It is recommended to improve the method by estimating delays on the roads without data.
2. The route set generation is now performed for every observation t, leading to high computation times. We recommend to study the option of

generating the route set per OD pair a priori, thereby reducing computation time and improving comparability, and to analyze its performance compared to the current method.

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