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Abstract

To understand the effects of incomplete information, we propose a novel multi-layer time-event-graph method to describe heterogeneous passengers' thinking about disposition time under different types of incomplete information: the time and location that passengers receive information, information contents, and passengers' belief on delay propagation (i.e. impacts of disposition timetable). The graph-based route choice describes passengers' behaviors with the impacts of incomplete information (perfect or on-route) and their belief (schedule-stubborn or delay-extended). The feasibility of passengers' routes and passengers' delays are analyzed. The results show that the on-route information causes more infeasible routes and larger passengers' delays (1.6min on average) comparing to the perfect information. The effects of passengers' belief with on-route information is negligible, while with perfect information, schedule-stubborn belief saves passengers' delay if information is no more than 25 min, otherwise delay-extended belief causes less passengers' delay.

Keywords

Incomplete information, Passenger belief, Real-time traffic control, Delay management

1. Introduction

Delays often occur in the operational business of public transit and usually make the scheduled timetable infeasible, e.g. signalling problems, late arrival of crew, construction work on the tracks (Bauer and Schöbel, 2014). Quality of service in the public transport network calls that are handled appropriately also situations of delays, disturbances or failures, trying to reduce the inconvenience caused to passengers despite the emergence of delays (Jespersen-Groth et al., 2009). To improve the quality of service of public transport, operating companies apply traffic management to provide more timely and accurate information to customers (Toletti, 2018) in case of delays. This information is the bridge to ensure the adjusted operations being disseminated to passengers, thus assisting individual passengers in coping with public transport delays. In an ideal situation, immediate and complete information (Corman, 2020) refers to a strict assumption that all the delays and the adjusted operations that have occurred and will occur in the network are able to be disseminated to passengers without any deviations. However, the information can be incomplete in reality due to the uncertainty of operation delays, the delayed dissemination of information channels, the habits of passengers checking the information about delays, etc.

The major goal is to study the effects of incomplete information to passengers' satisfaction in case of public transport delays, i.e. how to model passengers' behaviours under different incomplete information and quantify passengers' satisfaction. This problem is interesting and challenging to solve. First, the incomplete information refers to different aspects: the delayed information availability to passengers, the limited information content about specific public transport services at specific stations within specific time horizon, etc. For instance, Ben-Elia and Avineri (2015) review the literatures about inaccurate information under conditions of uncertainty, including information either before departure or once on the move. Second, passengers' belief matters their behaviours in the case of incomplete information. For instance, Arentze and Timmermans (2005) model passengers' belief about activity locations based on the limited information. Third, passengers' behaviours in the case of the incomplete information are different to that with the assumption of complete information. Parvaneh et al. (2014) mention that passengers are not always aware of all available alternatives with the uncertain information and updating beliefs.

The major contributions of the present paper are as follows:

(1) We propose to a novel multi-layer time-event-graph method to describe the incomplete information (e.g. information issue time, duration, information contents) and passengers' belief (e.g. schedule or delay beliefs) so as to evaluate passengers' behaviours on a schedule-based network in case of delays more realistically.
(2) The proposed multi-layer time-event-graph method is described with rigorous mathematical notations and formulas.
(3) The evaluation of different incomplete information cases is on a realistic case study in Dutch railway network.

This paper is structured as follows. Section 2 proposes a new method, named "multi-layer time-space-event graph" to present passengers' information and belief. The graph-based passenger route choice is explained. Section 3 explains the set-up of Dutch railway case study and analyses the results. In Section 4, conclusions and future work are presented.

2. Incomplete information and passenger route choice

In this section, we discuss the details of incomplete information in railway delay management, and explain passengers' belief in case of incomplete information. We also propose a novel method, named multi-layer time-space-event graph, to illustrate passengers' information and belief regarding to the original timetable and disposition timetable in real-time traffic control. The new graph-based passenger route choice is explained.

2.1 Incomplete information and passengers' belief

Passengers' information is how much they definitely know the published timetable (e.g. original, disposition) generated and disseminated by operating companies. The information can be complete or incomplete, whose completeness is determined by two factors from passengers' perspective: the one is what the information is (i.e. the features of information itself), including information's content (e.g. all trains' time at all stations, or one specific train's operation at some stations) and time horizon (e.g. till the end of the day, or till next hours); the other is when and where passengers receive this information (e.g. before their planned departure, or at the moment they arrive at the departure station). For instance, passengers can have complete information of the original timetable, including all the departure and arriving time at all the stations of all public transport services in the normal operations. While in case of public transport delays passengers might only have incomplete information of the disposition timetable, thus they partially know the operation time of some services at some stations. In some cases, passengers cannot be informed early enough, either the disposition timetable is not disseminated fast enough or passengers do not check the published information in time. In some other cases, the disposition timetable can show the information with limited content for a limited time horizon due to the lack of accuracy of future operations. These cases refer to the incomplete information in passenger-oriented delay management, in which passengers are not fully and timely informed about the delays that occur and the new generated disposition timetable in the network.

In case of incomplete information, passengers have to surmise the public transport operations (e.g. the departing or arriving time of some services at some stations) beyond the information time horizon based on the informed information content. This is called passengers' belief on delay propagation, shortly passengers' belief. The belief might be correct or not, whose correctness depends on its matching with the actual operations in reality. In general, passengers' belief is based on how passengers interpret the informed information, expect about the delays and consequences (e.g. continuous delay propagation or disappeared delays due to buffer time of original timetable), as well as foresee the possible public transport operations beyond the informed time horizon and stations.

In summary, the information represents the definite delays or the fixed disposition timetable from the moment that passengers know to a given definite time horizon. The belief represents what passengers believe about the indefinite delays and the unknown public transport operations from the end of information to the time passengers reaching their destination. Based on both the information and belief, each passenger comprehensively think about the public transport operations (especially the possible services related to their journey) in the case of delays, shortly called passengers' thinking in the present paper. In each passenger's thinking, his/her possible route choices are described by a set of "considered paths" (one, or usually more than one) linking the origin to destination, possibly including transfers at intermediate stations. Each "considered path" has a utility (e.g. travel time) to present passengers' satisfaction of this specific path. With the assumption that passengers are rational, they choose the maximum utility (e.g. the least travel time) in their thinking.

However, due to information's incompleteness and belief's incorrectness, passengers' thinking might deviate to the reality in the case of delays. In other terms, passengers' incomplete information and passengers' belief on delay propagation might affect their thinking about route choices, further affecting their actual route choice in reality. For instance, passengers might not know all the possible alternative paths (i.e. the set of "considered paths" does not include all the possibilities); or the considered paths exist some misleading deviations (e.g. arriving time) between passengers' thinking and the reality. Especially for passengers who need transfers at intermediate stations, the inaccurate time estimation may mislead passengers missing some feasible connections (i.e. the feeding train/bus departs later than the previous train/bus arrives). Therefore, passengers' chosen route with the "best" utility in their thinking might not always be the optimal one in reality.

2.2 Multi-layer time-space-event graph

In this subsection, we propose a novel method, named multi-layer time-space-event graph, to indicate passengers' information of original and disposition timetable, passengers' belief on delay propagation, their thinking of "considered paths" in a time-space network, and the possible deviations between passengers' thinking and reality. We use Figure 1 (a railway network) as an example to explain this new method, which can also be applied to other public transport similarly.

For the details, in Figure 1, the example railway network consists of four stations (i.e. station A, B, C, D), existing two physical routes from station A to station D: one physical route is A-B-D, the other is A-B-C-D. The subfigure (a) shows five example trains with different stop patterns, different line styles meaning different trains: Train 1 (loosely dashed line) is A-B-D, Train 2 (dotted line) is A-B-C-D, Train 3 (dashed line) is B-D, Train 4 (solid line) is A-B, and Train 5 (dash-dot line) is B-D.

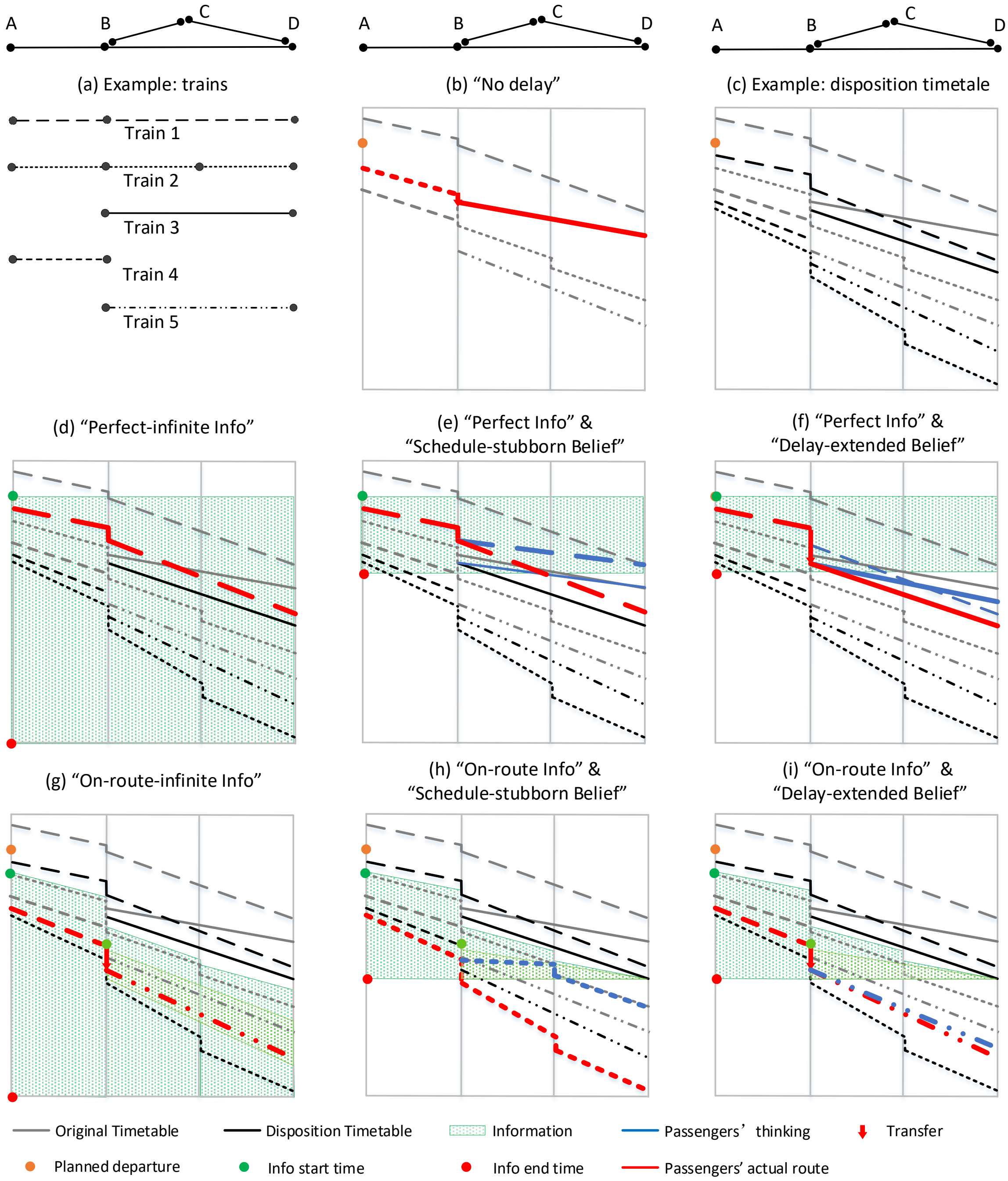

Figure 1: Explanation of incomplete information and passengers' belief

The graph in the subfigures from (b) to (i) in Figure 1 explains train's operation in a time (y-axis) – space (x-axis) network from station A to station D. The grey lines show the operations of the example five trains in the original timetable, e.g. subfigure (b); while the black lines show the five trains' corresponding operations in an example disposition timetable in the case of delays, see subfigure (c). We assume one passenger who plan to travel from the origin (station A) to destination (station D) with a given planned departure time (the orange node). In the case of "No delay", passengers know all the details of the original timetable and choose the fastest route to reaching destination. The red line in the subfigure (b) shows this passenger's initial plan, choosing Train 2 from station A to station B, and then transferring to Train 3 until station D.

In the case of delays, the green boxes in subfigures (d) to (i) indicate the set of events (e.g. trains' departure, arriving, and connection) in time and space for which information is available to passengers. X-axis describes which stations have available information, while y-axis shows how long time the information is available. The green and red nodes describe the start and end time of available information, respectively. We assume that operating companies could release the disposition timetable immediately after train delays via the media channels (e.g. mobile or station display). That means the start time (the green node) of available information depends on when passengers start to check the information. However, the time horizon of available information could be shorter or longer because the disposition timetable may change as consequence of succeeding delays. For instance, the subfigures (d) and (g) show the "infinite" available information, while the subfigures (e) (f) (h) (i) have a given end time (red node) of information.

The subfigures (d) to (f) show the instances of "Perfect information", meaning passengers perfectly know train delays and disposition timetable (i.e. all trains' departure and arriving time at all the stations throughout the whole network) within information's start and end time. This "Perfect information" may happen to the frequent users of mobile channels, who may often check the information about train delays and have a higher chance to know comprehensively the details of disposition timetable (i.e. trains' time-space events). Especially, the "Perfect-infinite information", subfigure (d), is the example that passengers are informed of all the train delays that will occur in the network until to their destination. With "Perfect information", the green box is always the shape of rectangle within a given time length of the provided information. The start time of information is the same as passengers' planned departure time, meaning the green node overlapping the orange node.

In contrast, the subfigures (g) to (i) show the instances of "On-route information", in which passengers could be aware of delays at the moment they arrive at specific stations (i.e. their planned departure station and the possible transfer stations) and partially know the rescheduled train services of disposition timetable related to these stations (e.g. depart from or stop at) within the given information time horizon. This "On-route information" may happen to some passengers who might not check the mobile channels very frequently, and rely on the information displayed at train stations. With “On-route information”, the green boxes are a series of trapezoid shapes within a given time length of the provided information. For each station, the information’s start time is the same as the time that passengers arriving at this station. Specifically, passengers’ start to know the information at the planned departure station (station A in Figure 1) at the same time as their initial plan (Train 2), meaning the green node the same as the time of Train 2 (the “No delay” route choice) in the original timetable in subfigure (b). For the following possible transfer stations (e.g. station B), passengers could know the information about trains departing from these stations after their earliest possible arriving time to these stations (the light green nodes).

Except the infinite information as in subfigures (d) and (g), passengers behave in the public transport network based on their belief on delay propagation beyond the information end time until the end of their journey. Passengers’ belief is an inference about the further delays, based on their available knowledge of the informed disposition timetable and the original timetable.

The subfigures (e) and (h) show the instances of passengers’ “Schedule-stubborn belief”, in which passengers believe that the informed delays will disappear in the subsequent stations and their trains will reach their destinations without any delay. This assumption makes sense because the buffer time exists in the original timetable and the trains might catch up their delays. For example, the blue line in subfigure (e), passengers know Train 1 has delays at station B, but they still believe this train will reach station D on time (the same time as in the original timetable).

The subfigures (f) and (i) show the instances of passengers’ “Delay-extended belief”, in which passengers believe that informed train delays will propagate among the subsequent stations. As an example, passengers assume the constant delays as the same amount as the delay at their last informed station. As is shown by the blue line in subfigure (f), passengers know the amount of Train 3’s delay at station B, and they believe this train will reach station D with the same amount of delays compared to the time in orginal timetable.

In the subfigures from (d) to (i), the blue lines show the time and space of the possible route between origin to destination in passengers’ thinking with the specific information and belief. The red lines show the actual time and space of the corresponding thinking route in reality (as in the disposition timetable), which is called “actual route” in this chapter. As is shown in these subfigures, within the time horizon of information, passengers’ actual routes match with their thinking (i.e. the red lines overlapping the blue ones), where the time and space are coincident with disposition timetable. Nevertheless, deviations might exist between passengers' thinking and actual routes if without information, depending on how much their belief differs from the disposition timetable.

We assume that at the moment the information disseminated, passengers immediately start their thinking and make their route choice with the rationality for minimizing travel time among all the thinking "considered paths". We explain the complexity and efficiency of the proposed multi-layer time-space-event graph method with different combinations of incomplete information and passengers' belief as follows:

Compared to "Perfect Information", the main different impact of "On-route Information" on passengers is the less "considered paths" because of the delayed information at passengers' planned departure station and the possible transfer stations. This comparison can be seen from the subfigures: (d) vs. (g), or (e) vs. (h), or (f) vs. (i). At passengers' planned departure station (station A), with "On-route Information", they might miss the trains which depart earlier than their planned departure time (orange node) in the original timetable but actually delay in the disposition timetable (e.g. Train 1) and depart earlier than they know this information (green node). Similarly, "On-route Information" might result in passengers missing some train connections; especially the trains that depart earlier than passengers' arriving time of the possible transfer stations (e.g. station B). For example, in subfigure (d), passengers' best route choice with the "Perfect-infinite Information" is Train 1. While in subfigure (g), with the "On-route-infinite Information", passengers miss this direct train (Train 1) due to not including this in their "considered paths"; subsequently they miss the train connection (e.g. Train 3) at the transfer station B because their arrive time with Train 4 is too late.

It has to be mentioned that, with other different delays or disposition timetables, there are also possibilities that either perfect or On-route information does not affect passengers' route choices, either at the planned departure station or the transfer stations, if there is no delayed earlier-departed train (e.g. Train 1) or passengers can arrive at the transfer station early enough.

In addition, the time horizon of information also affects the number of passengers' "considered paths". Here are two extreme examples: As the minimum, if passengers have zero information (meaning no green box in Figure 1), their "considered paths" do not include any possible alternatives of disposition timetable at all; while the "Perfect-infinite Information" has the largest set of "considered paths" based on the information of disposition timetable.

Moreover, information's time horizon, together with individual passenger's belief, also affects the correctness of "considered paths". That means the departure and arrive time at each station of one "considered path" are correct, as the same as in the real disposition timetable. For instance, in subfigure (e), passengers' thinking arrival time of Train 1 at station D differs from that in the actual disposition timetable, because of the lack of information about station D and their "Schedule-stubborn belief". With the limited information time horizon, it is hard for passengers to have a correct belief about future operations of every single train at each station.

However, this might not affect passengers' final route choice (see red lines in Figure 1) within the "considered paths" if they have appropriate belief. In other terms, the route (either direct train or multiple trains with connections) which passengers believe the earliest to arrive at the destination is indeed the fastest in reality. For instance, in subfigure (e) the incomplete information with "Schedule-stubborn belief", passengers can choose the same route, as the "Perfect-infinite Information" in subfigure (d), i.e. the optimal direct route (Train 1), even if the arrival delay at destination in reality are more than what they think. Similar results can also be seen with the comparison of subfigure (g) and (i), where passengers with "Delay-extended Belief" choose the best route.

There is also the possibility that the incomplete information and passengers' belief mislead their final route choice (red lines in Figure 1). We divide this misunderstanding into two categories. The first one is that the route passengers believe the earliest to arrive at the destination is indeed not the fastest, but still feasible, in reality. This kind of misleading might also result in the changes of passengers' transfers, stops, or even the physical route (such as changing from A-B-C-D to A-B-D). For instance, in subfigure (f) the incomplete information with "Delay-extended belief", passengers think Train 3 should reach station D earlier than Train 1, and choose the route with transfer from Train 1 to Train 3, which actually is not the fastest one in reality. Similar results can be found with the comparison of subfigure (g) and (h), where "Schedule-stubborn Belief" misleads passengers' thinking to choose a slower route.

The second misleading category is that passengers' thinking feasible route is actually infeasible in reality. This infeasibility can be caused by different reasons: some trains are cancelled in the disposition timetable, or some thinking feasible connections do not work (i.e. the feeding train/bus departs earlier than the previous train/bus arrives) in reality. For instance, in Figure 1, if passengers have zero information in the case of delays and they insist on their initial plan as in subfigure (b) (Train 2 from station A to station B, and then transferring to Train 3 until station D). In reality, this connection between Train 2 and Train 3 does not work anymore in the disposition timetable.

It has to be mentioned that, this kind of non-misleading or misleading passengers' thinking might happen to any combinations of the incomplete information and passengers' belief. It depends on multiple influencing factors: passengers' origin, destination and planned departure time, the train time deviations between disposition timetable and original timetable, the type and time horizon of incomplete information, as well as the correctness of passengers' belief. Briefly, this new proposed method, multi-layer time-space-event graph, can sufficiently describe these influencing factors and possible results of route choices.

3. Experiments and results

We perform a large set of experiments, based on the initial demand and various train delays of Dutch railway network presented in Corman et al. (2017). We test different cases with including different passengers' origin, destination and planned departure time, different delays, different incomplete information and passengers' belief, as well as different information time horizon. Passengers' behaviours and delays are analysed from the results.

3.1 Dutch railway network

The network, reported in Figure 2, comprises a significant region of the Netherlands, including Amsterdam, Schiphol and Utrecht. The traffic pattern we consider is the real timetable for year 2010, which is schematically reported in Figure 2, where every line is a service running twice per hour per direction. The network is highly interconnected and there are several bottlenecks. As a result, there is a need for frequent rescheduling in peak hours in case of disturbances, since any small delay may propagate to other trains with a domino effect.

As for the instances evaluated, we consider 20 instances with extended delays, generated with the Weibull distribution, fitted to real data, presented in Corman et al. (2017), per time horizon. Entrance delays, for all trains in the network, are defined based on a three-parameter Weibull distribution. In each instance, train delays are randomly generated according to a typical Monte-Carlo scheme. All computational results are reported as averages over this combination of 20 instances (when not aggregated at higher level). As is presented in Corman et al. (2017), there are 101 trains running on the network, with the average delay 37 seconds; 52.3% trains have a positive delay at the start of their trip; and 6.4% trains with a delay larger than 5 min at the start of their trip (a typical punctuality measure in railways).

The OD pairs considered in the experiments are based on the average volume of passengers at the considered stations as published by the infrastructure manager, as presented in Corman et al. (2017). Triples odw in ODW are generated by considering the largest 22 OD pairs in the network, for different time windows. Each odw has a number of passengers.

For the 20 delay instances and the mentioned passengers ODW, we test the two types of infinite information (i.e. "Perfect-infinite Information" and "On-route-infinite Information") as well as the four combinations of passengers' information and belief mentioned in subsection 5.2.2 for different time horizon of incomplete information.

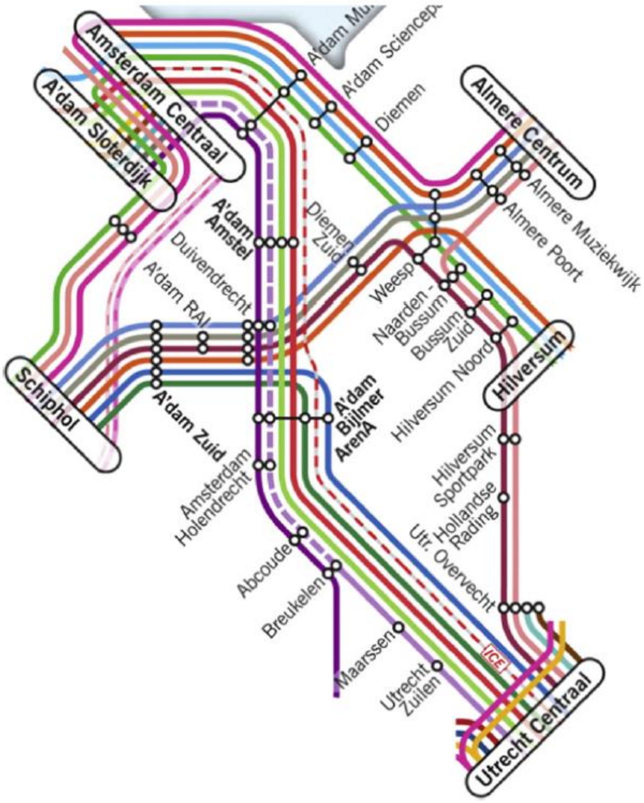

Figure 2: Test case infrastructure description (elaboration from sporenplan.nl)

3.2 Infeasible routes

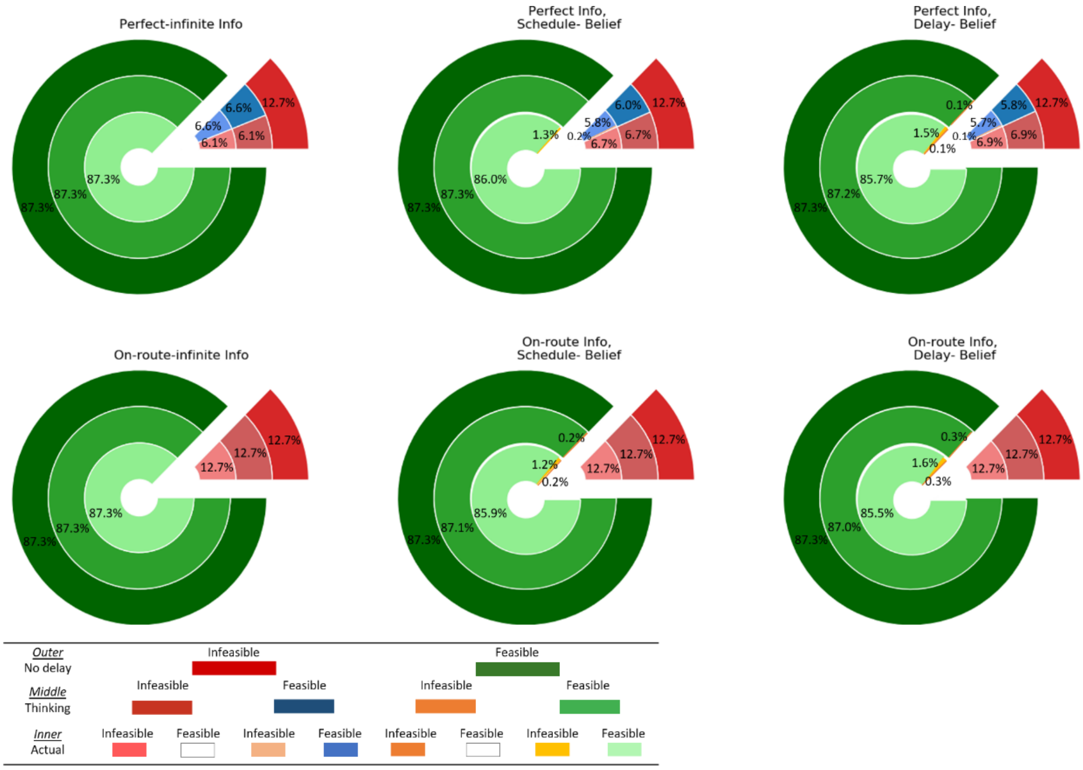

Figure 3: The average percentage of feasible/infeasible routes, comparing different information and belief types

Figure 3 shows the average percentage of feasible/infeasible routes in the tested 20 delay instances, comparing different information types (perfect or on-route) which are infinite, or incomplete with different belief types (schedule-stubborn or delay-extended). For the incomplete information, different time horizon cases varying from zero to infinite are tested and calculated on average.

In each subplot of Figure 3, there are three layers to show the percentage of route feasibility: in the case of “No delay” (the outer layer), in passengers’ thinking (the middle layer) based on defined infinite or complete information, and in the actual disposition timetable in reality (the inner layer) due to the corresponding thinking. As is shown in the legend, different families of colours are to mark the changes of route feasibility. The family of green colours means always feasible in the three layers; the family of red colours shows always infeasible in the three layers; the family of blue colours shows the routes get feasible from infeasible from outer layer to inner; the family of orange colours means the routes get infeasible from feasible from outer layer to inner.

For each layer, the total percentage is 100%. The result of “No delay” (the outer layer) is consistent in each subplot: 87.3% routes (dark green) are feasible; 12.7% (dark red) are infeasible because of the passengers who has a late departure time, wanting to take the last train or missing the connection to their destination.

First, we check the feasible routes of “No delay” (dark green). Thanks to the infinite information of the disposition timetable, i.e. both “Perfect-infinite Information” (top left) and “On-route-infinite Information” (bottom left), all of these routes are also feasible both in passengers’ thinking (green) and in reality (light green) in case of delays. If the information is incomplete (the four subplots on the right), most routes (more than 99%) are still feasible in passengers’ thinking (green in the middle layer); however, around 2% of theses thinking feasible routes are actually infeasible in reality (orange and yellow in the inner layer) due to the misleading incomplete information plus passengers’ wrong belief.

Specifically with the same type of belief, passengers suffer slightly more infeasible routes (less than 1%) in case of “On-route Information” (bottom middle or right) comparing to “Perfect Information” (top middle or right). With the same information type, the “Delay-extended Belief” (the two subplots on the right) causes a bit more infeasible routes (less than 1%) than “Schedule-stubborn Belief” (the two subplots in the middle).

Then, we check the infeasible routes of “No delay” (dark red). With the “On-route Information” (the bottom three subplots), all of these routes are infeasible, either in passengers’ thinking or in reality. This is for the reason that passengers who think they do not have feasible route in “No delay” will not go to the station to check the information of train delays in case of “On-route Information”. In contrast, with the “Perfect Information” (the top three subplots), approximate 50% of these infeasible routes (“No delay”) significantly become feasible (the family of blue colours). That means some train delays together with the “Perfect Information” can result in benefits on route choices, meaning either proper train services or appropriate connection, of passengers who has a late departure time.

Specifically, “Perfect-infinite Information” (top left) gives the most benefits, 52% infeasible routes in “No delay” get feasible in both passengers’ thinking (blue) and the actual disposition timetable in reality (light blue). If passengers have incomplete “Perfect information”, “Schedule-stubborn Belief” (top middle) results in slight more feasible routes (around 2%) comparing to “Delay-extended Belief” (top right) in passengers’ thinking (blue). In both the two subplots, there are very few routes (around 0.2% of the total amount of routes) are infeasible (light orange) in the actual disposition timetable in reality.

3.3 Passengers' delays

To study passengers' delays, we filter out the passengers whose thinking and actual routes are both feasible, as shown with the family of green colours in Figure 3.

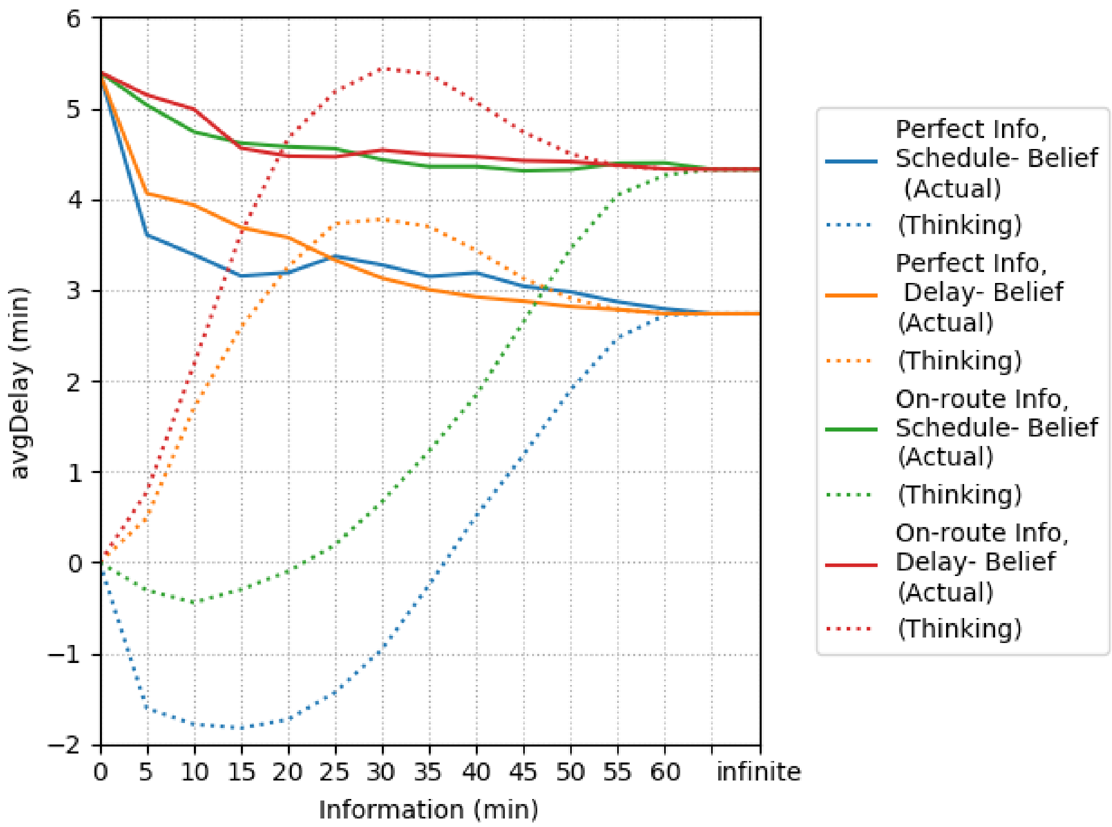

Figure 4: The average passengers' thinking delay and actual delay with different information time horizon

Figure 4 shows the trend of passengers' average delay (y-axis, min) both in their thinking (dotted line) and in reality (solid line) following the increasing information time horizon (x-axis, min). The four colours report the combinations of two incomplete information types and two belief types.

If passengers have no information of train delays (information is zero), they think they will not delay (average delay is zero) but they will suffer the largest average delay (5.4 min) in actual train operations. Overall, passengers' actual average delay in reality (solid lines) decreases with the increase of the disseminated information. Specifically, the

“Perfect Information” always leads to less average delay in reality, comparing to the “On-route Information”, at any information time horizon no matter of passengers’ beliefs. With the infinite information, the benefit of “Perfect Information” on reducing actual delays gets maximum to 1.6min.

The gap between the red and green solid lines is small, around 0.1min, meaning passengers’ belief does not matter too much with “On-route Information” in real life cases. In contrast, the gap between the blue and orange lines is larger, meaning passengers’ belief do affect their actual delays in case of “Perfect Information”. Specially, if passengers do not have enough (less than 25min) information, “Schedule-stubborn belief” leads to a less delay, around 0.6min on average; while if they have enough (more than 25min) information, “Delay-extended Belief” is slightly better to passengers, saving around 0.2min on average.

With “Schedule-stubborn belief”, passengers could do the optimal choice (blue or green solid lines) with proper information, but they will be pissed off, as they believe they should have less delay (blue or green dotted lines). This connects to behavioural findings; which means the operating companies can just tell the passengers that they actually did the best they could have done in the case of train delays. In addition, with “Schedule-stubborn belief”, passengers even think they could have negative delays, comparing to their planned arriving time at destination based on original timetable (off-line schedule) within 36min (blue dotted line) and 20min (green dotted line) information for “Perfect Information” and “On-route Information”, respectively.

In contrast, with “Delay-extended belief”, passengers might be pessimism about train delays, meaning their thinking is worse than actual delays in reality, if they have sufficient information such as after knowing 19min (the intersection of two red lines) and 22min (the intersection of two orange lines) information for “On-route Information” and “Perfect Information”, respectively.

With any given time horizon of information, “Perfect Information” always results in less passengers’ thinking delay than “On-route Information” in any type of belief. From the figure, we compare the dotted lines: the red is always larger than the orange and the green is larger than the blue.

With the same type of information, with a limited information time horizon, the “Delay-extended Belief” results in a larger thinking average delay than the “Schedule-stubborn Belief”. From the figure, we compare the dotted lines: the red is always larger than the green and the orange is larger than the blue.

Nevertheless, if the information is infinite, passengers' thinking delay is not relevant with belief any more. In fact, with infinite information, passengers' thinking delay (the dotted lines) is the same as the actual delay (the solid lines) in reality, which only depends on the types of information.

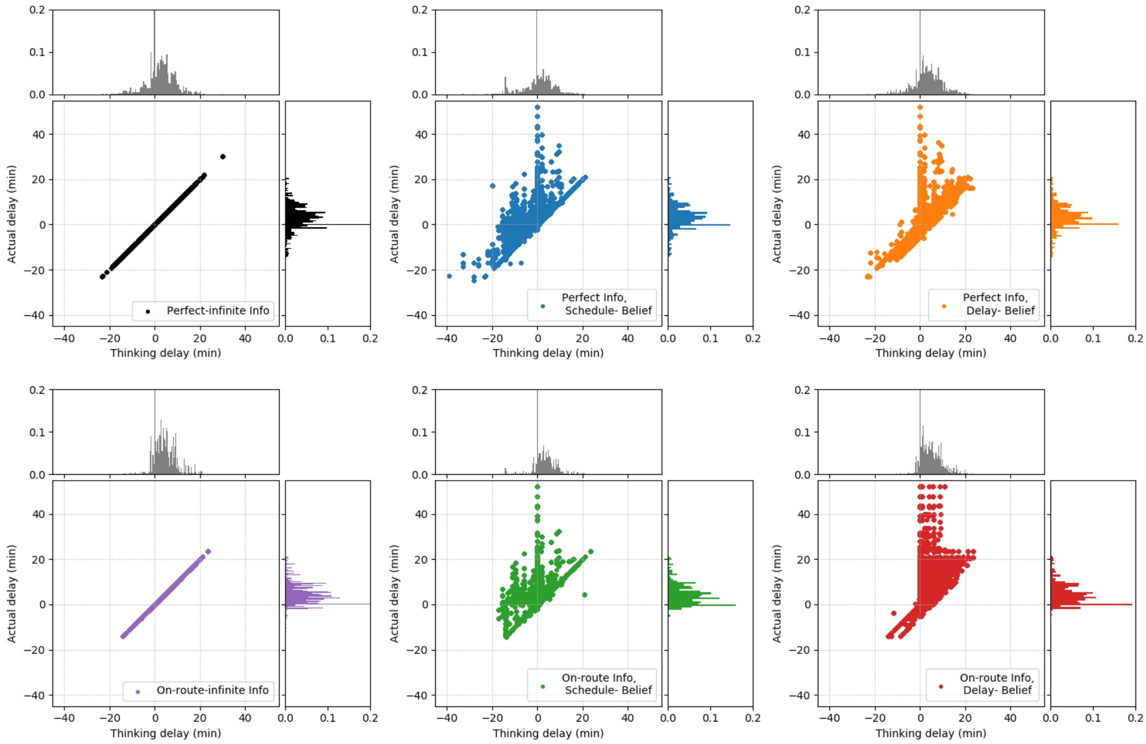

Figure 5: Passengers' thinking delays vs. actual delays, comparing different information and belief types (Incomplete information time horizon: possibilities from zero to infinite)

The bi-axis scatter plots in Figure 5 display the thinking delay (x-axis, min) and actual delay (y-axis, min) for each individual passenger in different information cases (in different colours), including the results of different time horizon varying from zero to infinite. The two histograms at the sides of each scatter plot are the probability density of passengers' thinking delays (grey colours) and actual delays (same colour as the scatter) of different information cases.

With the infinite information, a consistent correlation between passengers' thinking delay and actual delay is shown in a slash line in the left two scatter plots. The "Perfect-infinite Information" (top left) causes more passengers having the negative delays in reality comparing to “On-route-infinite Information” (bottom left): one proof is that the least delay (black) is less than -20min, further less than the least delay in purple colour; the other proof is the larger delay distributions between -20min to 0 in the black colour.

As is seen from the right four plots, with the finite information, there are passengers whose thinking delay is the same as the actual delay, same as the slash line in infinite information. However, many other passengers exist whose actual delays (y-axis) are larger than their thinking delays (x-axis), shown in the scatters upper than the slash line, among which many passengers have think they will not have delay (zero, in x-axis) actually have positive delay (y-axis) in reality. Especially with “Schedule-stubborn Belief” (blue and green), most passengers underestimate the delays in their thinking. While with the “Delay-extended Belief”, we can also figure out some scatters below the slash line, meaning some passengers overestimate the delays in their thinking. The deviations of this overestimation are not too much to the slash line.

Passengers’ thinking delays (x-axis, grey distributions) depend more on passengers’ belief based on their known information, usually “Delay-extended Belief” (the right two plots: orange and red) resulting in more thinking delays comparing to “Schedule-stubborn Belief” (the middle two plots: blue and green).

However, in reality, passengers’ actual delays (y-axis, colourful distributions) depend more on the disseminated information rather than their beliefs. With “Perfect Information”, the blue and orange distributions have a longer trail between -20min to 0, meaning more passengers can have negative actual delays (y-axis), comparing to the “On-route Information” (green and red).

4. Conclusions and future research

We study the problem of the incomplete information and its effects to passengers’ route choices in case of public transport delays. We propose a new multi-layer time-space-event graph method and explain the graph-based route choices to describe passengers’ behaviours with the incomplete information and passengers’ belief in public transport delays, where the graph includes five layers: original timetable, disposition timetable, information, passengers’ thinking and passengers’ actual route choice. We define and discuss two types of incomplete information, i.e. “Perfect Information” and “On-route Information”, and two types of passengers’ belief: “Schedule-stubborn Belief” and “Delay-extended Belief”. The information time horizon is also considered, from zero (i.e. no information) to infinite. Passengers’ route feasibility and passengers’ delay in both their thinking and in reality are studied to understand the effects of incomplete information.

The results show that the “Perfect Information” helps passengers to take the delayed earlier-departure trains and connections, which can offering about 50% more feasible routes and decreasing passengers’ delays compared to “On-route Information”. The largest gap of these two information types is 1.6min on average when the information is infinite. In case of “On-route Information”, the different effects of passengers’ beliefs on their delays is negligible. However, beliefs indeed affect passengers’ delays depending on the information time horizon. When information is not enough (no more than 25min), “Schedule-stubborn Belief” cause fewer passengers’ delays (0.6min on average) in reality. In this case, passengers might not satisfy with the public transport delays because they believe less delays, even zero delay or negative delays in their thinking. Otherwise when information is enough (more than 25min), “Delay-extended Belief” cause fewer actual passengers’ delays. With the “Schedule-stubborn Belief”, passengers’ thinking delays has a large gap to the actual delays in reality if the information time horizon is short. The longer the information time horizon, the less gap between passengers’ thinking delays and actual delays. In contrast, passengers can overthink the delays (i.e. actual delays less than thinking delays) with “Delay-extended Belief”.

Based on the proposed multi-layer time-space-event graph method, more research can be extended. For instance, it can be applied to severe public transport disruptions, such as physical route infeasible, route blockage for a certain long time or multiple train cancellation, where the incomplete information and passengers’ belief may lead to more missing connections or infeasible routes. For the research field about uncertain delays or disruptions, the information might need to be provided multiple times, resulting in different possibilities of passengers’ thinking, which can be studied based on the proposed method.

Moreover, combining the proposed method with timetable or rolling stock rescheduling is able to tradeoff the benefits and costs of information and public transport operations. This research enrichs the passenger heterogeneity on the aspects of their type of belief, which can be applied as one attribute in the agent-based simulation with the efforts of more data collection and calibration and the study about computation efficiency.

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