Model of heterogeneous passengers’ rerouting behavior under metro operational disruption

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Abstract. This paper presents a framework to identify affected commuter passengers and their rerouting decisions under metro operational disruption. A cumulative prospect theory (CPT) based model is proposed to capture commuters’ mental activity and behavior from individual perspective considering heterogeneities, including time value, requirement of arrival time, sensitivity of cost and attitudes toward risk. Thus, commuters’ rerouting decision among multiple modes such as metro, bus, taxi and walking, can be effectively and accurately identified, which successfully overcomes the limitation of simplification and assumption in traditional methods. Case study of Beijing metro network and corresponding data of Automatic Fare Collection System (AFC) under disturbance in real world proves the effectiveness of the presented method.

1. Introduction
On weekdays, the distribution of commuter passenger flow in metro network is predictable. Some of the commuters’ regular route may become unavailable due to station closure or train service failure. Once received the failure information, passengers will adapt their regular routes based on travel experience and travel information. The commuters’ rerouting behavior generates new patterns of flow aggregation and distribution in the metro network and other modes of transportation.

Passenger’s rerouting behavior under metro operational disruptions has been considered as an important factor in recent study of timetable adjustment, metro network robustness and vulnerability. Alicia [1] assumed three alternatives of passenger routes during metro service failure to measure overall travel time of a network. Luis Cadarso [2] proposed a two-step approach to adjust the timetable and the rolling stock assignment, considering passengers’ reaction to the disruption. Daniel (Jian) Sun [3] proposed to measure the metro network vulnerability by assuming the passenger flow redistribution follows an all-or-nothing assignment rule.

Passenger rerouting behavior under metro operational disruptions is a problem of decision-making under uncertainty or risk. CPT has been widely used on commuter decision-making modeling. Xu [4] presented a method to set the reference point value considering the commuter’s requirement of travel time reliability. Results deduced using CPT were more consistent with experimental data than EUT-based route choice models. Jon [5] found that travelers’ decision depends on their own reference points. Gao [6] presented an adaptive route choice in risky traffic networks, results demonstrate the flexibility of the CPT model to represent flexible attitudes toward risk presented a routing policy choice model based on CPT, where flexible attitudes toward risk were captured. Results demonstrated that CPT is...
more general than EUT in explaining decisions under risk. Li [7] designed heterogeneous reference points for dynamic route and departure time choice model. Travelers’ bounded rationality was depicted based on CPT. Therefore, CPT has been proved is effective in decision modeling of commuters with heterogeneity, which provides an approach to detailed depiction of passengers’ rerouting behavior under metro disruption.

2. Problem description

The “operational disruptions” studied in this paper emphasize the short-term or long-term disruption of the metro network capability. Operational disruptions can be reflected in the Short-turn routing or the speed limit operation of the train and the station closure. For commuters who still outside of the metro station or commuters that have been affected by disruption in the metro network, after sensing, receiving or inquiring operational disruption information, other modes of travel, travel routes, etc. They combine travel experience and travel preferences to choose the origin station, destination station and travel route of the trip. Commuters may abandon the metro to choose other modes of travel, continue to choose the metro and wait until the failure recovered or continue the trip around other metro routes. Affected by the metro service failure, the commuters’ rerouting behavior generates new patterns of flow aggregation and distribution in the metro network and other modes of transportation.

For the operational disruption’s measures, the metro physical network and the train service network are reconstructed first, and the reconstructed network parameter set is extracted, including the basic data such as nodes, sections, train transportation capacity and train delivery headway. By locating decision-making location and time of passengers affected by the failure, rerouting alternative route set can be obtained. Modeling the rerouting decision based on the cumulative prospect theory and generate alternative route set. Based on the reconstructed network parameter set and the rerouting alternative route parameters, deduction of passenger flow distribution after the disruption can be done.

3. Commuter passenger rerouting behavior modelling

3.1 Locating affected passenger’s decision-making location and time

During the early rush hours of the working day, commuter passengers have stable departure time and travel route, so the set of affected passengers can be selected by using historical travel data to screen passengers pass through the failure section during the same period of normal weekday. In this paper, based on AFC data and train schedules to build a time and space expansion network, assign each inbound passenger to the train on the time-space network.

By combining expansion network with the train operation map, the number of train that the passengers inbound can be found. The decision-making time of passengers in station and on train is time of failure, decision-making location is the station when failure occur and next stop station. Passengers outside the station, decision-making location and time is the time of passengers outside the station ready to enter and the station ready to enter.

3.2 Passenger rerouting alternative route set

There are 5 types of the rerouting alternative route under operational disruption: (1) Waiting for the disruption recovery; (2) Choose other routes inside the Metro; (3) Change the origin station by using other type of transportation; (4) Change the destination station then using other type of transportation; (5) Choose bicycle, taxi, walking, bus.

When the operator takes different countermeasures and the failure section is different in the position of the passenger's itinerary, the passenger has different alternative routes. Due to the high reliability of travel time in the metro network, the same OD in the same time period has a strong regularity on the travel time of the same route. Therefore, the historical travel AFC data of same segment of the route is used to estimate the travel time distribution of the alternative route (1) and (2). For alternative route (3), (4), and (5) belong to other modes of transportation, the travel time distribution of the route is obtained
by using online travel planning software. After the travel mode selection is determined, the corresponding travel costs are determined too.

### 3.3 Passenger rerouting behavior model based on cumulative prospect theory

To apply the cumulative prospect theory to construct a rerouting decision-making model, it is necessary to combine the special needs and characteristics of commuter passengers in rerouting behavior under sudden failures, including:

1. Subway commuter passengers should be considered as individuals with heterogeneity.

   Due to the difference in time value, commuter passengers have different requirements on the strictness of the time to reach the destination, the attitude towards possible risks, and the sensitivity to different path costs, which in turn affects the rerouting decision. In this paper, commuter passengers are classified according to the difference in time value, and there are differences in the rigor and risk preferences of various types of passengers to the destination time.

2. The reference point selection is based on the original path time cost.

   During the disruption, the choice of the passenger reference point is related to the travel time and cost of the original route, because that factors reflect the passenger's request for the expected arrival time. Based on the psychological and behavioral characteristics of commuters, this paper proposes a reference point model with two reference points considering the heterogeneity of commuters based on the original route travel time and cost (Figure 1).

![Figure 1. The commuter reference point](image)

By using time value of the commuters convert the travel time into travel costs, the commuter expects the travel cost interval to be $[u_p, u_q]$:

$$u_p = U_0 + t_1^w \cdot \theta_{tr}^w$$

$$u_q = U_0 + t_2^w \cdot \theta_{tr}^w$$

(1)

Where $u_p$ is commuter expects travel cost of early arrival time reference point $t_1^w$; $u_q$ is commuter expects travel cost of late arrival time reference point $t_2^w$; $U_0$ is original route travel cost in the metro network and $\theta_{tr}^w$ is time value of $w$ commuters.

3. The value function reflects the behavioral characteristics of commuter passengers “avoiding the risk of gains and pursuing the risk of losses”.

   The value function converts objective gains or losses into the subjective value of commuter passengers. When the $w$ commuter chooses the $k$ type of travel mode, if the arrival time is earlier or later than the reference point, loss will occur and consider the penalty.

   Since the rerouting behavior under the operational disruption is a decision-making behavior under risk conditions, the results will be different of the passenger selection route with different attitudes toward risk. The value function as shown in Equation 3.
\[ v(u_k^w) = \begin{cases} 
-\beta_1 (u_p - u_k^w)^{\eta_w} & u_k^w < u_p \\
\beta_2 (u_k^w - u_p)^{\eta_w} & u_p \leq u_k^w < u_0 \\
\beta_3 (u_q - u_k^w)^{\eta_w} & u_0 \leq u_k^w < u_q \\
-\beta_3 (u_k^w - u_q)^{\eta_w} & u_q \leq u_k^w 
\end{cases} \] (3)

Where \( v(u_k^w) \) represents the value of the \( w \) commuter’s choice of \( k \) type of travel mode; \( \eta_w \) is the attitudes toward risk of \( w \) commuters; \( \beta_1, \beta_2, \beta_3 \) and \( \beta_4 \) are loss-aversion coefficients, using Hanqi Wang calibration results[8] value of gain is \( \beta_1 = \beta_2 = 1 \), and value of loss is \( \beta_3 = 2.25 \).

(4) Commuters pay attention to small-probability events when making route decisions during disruption

The weighting function converts the objective probability of the route travel cost into the subjective probability of the passenger. Commuters pay attention to small-probability events when making route decisions during disruption, and often subjectively exaggerate the probability of unlikely events, while ignoring high-probability events.

Combined with the calculation of the value function of \( w \) commuter chooses the \( k \) type of travel mode, the commuter’s travel cost obeys the piecewise normal distribution, and the travel cost distribution function is a continuous function, after integrated, the prospect value of the route is as shown in Equation 4.

\[ V = v_1 + v_2 + v_3 = \int_{u_k^w}^{u_k^w + \theta_k^w} \frac{d\omega \cdot F(u_k^w)}{du_k^w} \cdot v(u_k^w) du_k^w + \int_{u_k^w}^{u_k^w + \theta_k^w} \frac{d\omega \cdot (1 - F(u_k^w))}{du_k^w} \cdot v(u_k^w) du_k^w + \int_{u_k^w}^{+\infty} \frac{d\omega \cdot F(u_k^w)}{du_k^w} \cdot v(u_k^w) du_k^w (4) \]

4. Case study

Taking an operational disruption of Beijing Subway as an example, Wukesong Station of Beijing Metro Line 1 (towards the direction of Sihui East) experienced an operational disruption at 7:05 am, resulting in the interruption of normal operation activities in the “Wukesong- Wanshoulu” section.

During the disruption, Beijing Metro operator used the Gongzhufen Station as the starting point and the end point of train operation. The “Pingguoyuan - Wanshoulu” section of the station was closed, no train was running until the failure was eliminated at 7:55 (towards the direction of Sihui East) in the morning, and the line operation returned to normal.

Therefore, the prospect values of the respective routes are calculated for different types of passengers having different OD pairs whose decision time and decision location are same, and the passenger selection result at each decision time is obtained. Determining when passengers back to the metro station and when they leave by using the passenger’s route adjustment result and the travel time distribution of the route, combined with the unaffected passenger route, the matrix of the number of people entering and leaving the station during each time period after failure is obtained, and the distribution of the passenger flow of the metro network after the failure occurs can be derived.

4.1 Rerouting model verification

AFC data on the period of operational disruption are used to compare with output data of the presented model. Feasible alternative routes for commuter passengers during the disruption include: changing the
origin station, changing the destination station or abandoning the metro to select other modes of transportation.

4.2 Changing the origin station.
Number of entering passengers in the failure period obtained by this model are basically consistent with the AFC data of Wukesong Station (Figure 2). Entering passengers remarkably increase at 8 am when service is normal.

As the Wukesong-Wanshoulu section is closed, commuters whose regular origin station were Wanshoulu may tend to transfer to the nearby Gongzhufen Station (Figure 3). Data comparison shows the effectiveness of the presented model to capture passengers’ behavior of changing origin station.

4.3 Changing the destination station or abandoning the metro to select other modes of transportation
Commuters may have to change their regular destination station and select other transportation modes due to the disruption. Data comparison of Wukesong Station (Figure 4) and Wanshoulu Station (Figure 5) indicates the destination adjustment and metro abandoning behavior.

In general, the model of passengers’ rerouting behavior can more accurately describe passenger flow in the event of a metro disruption, and provide basic data support for the passenger flow organization under metro operational disruption.

5. Conclusions
The commuter rerouting model presented in this paper provides an available approach to accurate quantization of passenger redistribution and evolution under operation disruption in metro network. Commuter’s mental activity and behavior are described from individual perspective considering heterogeneity, which successfully overcomes the limitation of simplification and assumption in traditional methods.
The three difficulties addressed in this paper are as follows. First, commuters affected by disruption make their decision at different locations and times, which need to be identified precisely. Second, alternative routes (multi-mode) for a commuter depend on detailed position of his/her commute trip, which means decision at beginning or end of a commute trip should be different. Third, commuters’ decision differs from each other due to individual differences on time value, risk attitude and requirement of arrival time. Thus, accurate passenger redistribution can be obtained by the presented model to support timetable adjustment, bus or taxi dispatching or safety protection at stations according to irregular passenger flow under operation disruption.

Acknowledgments
This research is supported by Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University (K201904) and the Fundamental Research Funds for the Central Universities (2018JBM031).

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