Space-time accessibility and equity in multimodal supernetwork: a case study in Rotterdam-The Hauge metropolitan area

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SHORT SUMMARY

Space-time prism (STP) is an essential concept in time geography and has been predominately constructed in unimodal transport networks. Because of the vast trip chaining options by private vehicles and public transportation, it was challenging to construct STP over multimodal transportation networks. An efficient method has been put forward to narrow down the action space for trip chaining and construct STP efficiently in a multimodal supernetwork. This study applies the multimodal STP modeling for space-time accessibility and equity analysis with two accessibility indicators and two equity metrics to examine for a common activity in the Rotterdam-The Hague metropolitan area, the Netherlands. We found that multimodal trip chaining improves accessibility, especially for those without a car. Based on the accessibility indicators, Gini coefficients and the 20:20 ratios of the 20% richest people and 20% poorest people show that the study area has low inequity, and multimodal trip chaining can improve equity.

Keywords: accessibility; equity; multimodal supernetwork; space-time prism

1. INTRODUCTION

The uneven urbanization results in the growing interest in accessibility and equity measurement for individuals from different social groups. Emphasizing individual constraints in space and time, space-time prism (STP) delineates opportunities individuals can reach under their time and space budgets (Lenntorp, 1976). The projected STP on the planar space is called potential path area (PPA), covering physical locations of accessible opportunities.

The classical STP applies uniform maximum travel speed through space and time, which would overestimate the accessibility because of ignoring the speed variations. Researchers have noticed this drawback and have extended the STP modeling to improve the realism of STP modeling in transport systems. Miller (1991) proposed the network-based time prism (NTP), allowing speed changes in network links. Following this work, STP modeling has been extended in different dimensions, as reviewed in Liao (2019).

Accessibility is defined as the ability for an individual to travel and take part in activities and the time available for activity participation at locations, specifying the importance of space and time in individual accessibility measures (Miller, 2017). Existing literature has extensively examined accessibility, divided into four categories as summarized by Geurs and van Wee (2004). Space-time accessibility is a fundamental indicator of individual mobility underlies equity measures. Equity refers to the proper distribution of resources between diverse social groups. Depending on the equity standard, equity can be categorized into two types: horizontal equity and vertical equity. While vertical equity states that those who need most should get more, horizontal equity requires that resources be equally distributed among the social groups or areas. Gini coefficient has been widely used to measure inequality of income distribution among the population of a country, and the Lorenz curve shows the cumulated income over cumulated population following increased share of income. The Gini coefficient and Lorenz curve are adopted in the transportation field to evaluate equity and social exclusion effects among accessibility (Pritchard et al., 2019). However, some argue that the Gini coefficient is insensitive to the top and bottom of the income spectrum (De Maio, 2007). For that matter, alternative inequality measures, such as the 20:20 ratio, are suggested as a complementary indicator for the Gini coefficient (Liu et al., 2022).

While most space-time accessibility measures in the STP model are restricted to using a single private vehicle (PV), a few studies have attempted to add walking or public transportation (PT) as the complementary mode. Although their works have enhanced the accessibility measures in the STP model towards multimodal transportation systems, the ignorance of flexible trip chaining between PV and PT (PV+PT) still leaves much space for improvement. The enormous trip chaining combinations of PV+PT lead to make it a challenge to measure STP-based accessibility in the multimodal transportation system. Qin and Liao (2021) suggested three incremental strategies to eliminate PV+PT options that contribute little to enlarging STP and PPA in multimodal transportation networks. Their method was proved to be an efficient tool for measuring STP-based accessibility in a multimodal supernetwork.

This paper applies the multimodal STP modeling to evaluate accessibility and equity in a large-scale multimodal transportation network. For the sake of consistency, we adopt the two common accessibility indicators suggested in Qin and Liao (2021) and further incorporate them in two equity metrics, i.e., Gini coefficient and 20:20 ratio, for a common activity. In this short paper, we consider shopping as the primary activity and the Rotterdam-The Hague metropolitan area as the study area using a sample of the real population. The results show that individuals can benefit from the multimodal trip chaining, and those without cars can benefit more than their neighbors. Gini coefficients and 20:20 ratios indicate that the study has low inequity, which can be further improved by the multimodal trip chaining.

The remainder of this paper is organized as follows. Section 2 first briefly introduces the multimodal STP modeling and then formalizes the space-time accessibility equity measures. Section 3 shows the results of the case study. Section 4 concludes the paper with a summary of the contributions and plans for future work.

2. METHODOLOGY

In the first subsection, we briefly introduce the methods for eliminating the unpromising PV+PT trip chaining options for constructing STP in a multimodal transportation network represented as a multimodal supernetwork. The second subsection gives the formulations for two accessibility indicators and two equity metrics based on the STP modeling.

2.1 STP modeling in multimodal supernetwork

Supernetwork is an integration of different types of networks (Figure 1). Following Liao et al. (2013), the multimodal transportation network is classified into private vehicle network (PVN) and public transportation network (PTN). In the supernetwork modeling, every network is labeled with an activity state *s* (0: unconducted 1: conducted) and a vehicle state *p* showing if the car is using or parked at a parking location. Thus G_{sp}^{PT} and G_{sp}^{PV} represent the PTN and PVN, respectively, where PV is a set of private vehicles, e.g., PV= {bike, car}. The multimodal supernetwork is built by connecting the PTNs and PVNs across every possible combination of activity and vehicle state. Nodes in supernetworks represent physical locations in the real world. A node *n* in the supernetwork is associated with an activity state and a vehicle state as $n|_{sp}^{m}$ where $m \in \{\mathrm{PT}, \mathrm{PV}\}$. Links in supernetworks are defined as transaction links, transition links, and travel links. The physical movements between nodes in the PVN and PTN are represented as travel links. Any feasible space-time path from origin h_0 to destination h_1 indicates individual movement to participate in the activity, where h_0 and h_1 are the anchor nodes for STP modeling.

The vast possibilities in PV and PT combinations make it infeasible to construct STP in the multimodal supernetwork. In the PV+PT trip chaining, the transfer between PV and PT requires a parking location for PV. Since each PT stop has a parking location nearby, the problem is limited to selecting promising PT stops in constructing STP.

Qin and Liao (2021) proposed three incremental strategies that can efficiently construct STP with little compromising the accuracy of accessibility measures. First, an upper bound PPA applying maximum travel speed delineates all potential PT stops. Three transport modes (bike, car, and PT) are considered at average maximum travel speeds following the relationship, as $v_{\mathrm{bike}} < v_{\mathrm{PT}} < v_{\mathrm{car}}$. PT stops outside the PPA associated with the car are excluded in this step. Second, the study area is partitioned based on grids whose dimension depends on the average travel speed of PV to construct STP. PT stops in the same partitioned area are treated as competitors, and at most one PT stop is selected within the same area. Attractiveness and service buffer are two factors that influence the heuristic selection. Attractiveness is defined as the count of PT lines that goes through corresponding PT stops, and the service buffer is PT-stop centered and PV-dependent. All selected PT stops represent their partitioned areas and construct the multimodal STP together. Third, the selected PT stops are further pruned by the triangular inequalities, inspired by the Euclidean geometrical principles. With these strategies, only a compact but useful set of PT stops are selected for PV+PT trip chaining, with which the multimodal supernetwork is constructed, and an existing two-stage bidirectional search method (Liao, 2021) can delimit the STP and PPA.

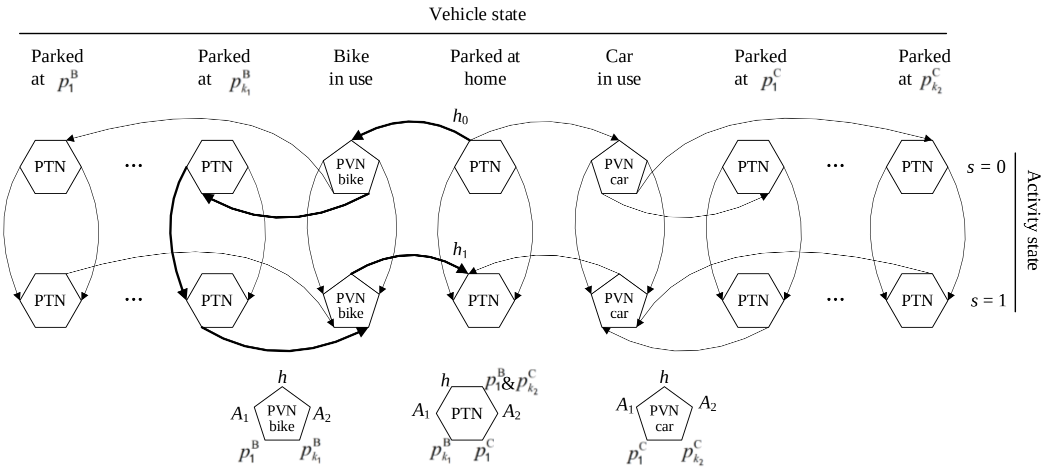


Figure 1 Multimodal supernetwork (Qin and Liao, 2021).

As a result, a node inside the STP must satisfy Eq. (1) as

$$\tau(h_0, n|_{0p}^{m}) + d_a + \tau(h_1, n|_{1p}^{m}) \leq t_B \tag{1}$$

where $\tau(\cdot,\cdot)$ is the travel time between two nodes in the supernetwork, d_a is the minimum activity duration, t_B is the time budget. Eq. (1) can be solved by twice one-to-all shortest path searches from h_0 and h_1, respectively.

2.2 Space-time accessibility and equity

This subsection gives the formulations of two accessibility indicators and two equity indicators based on STP accessibility. Based on Eq. (1), two accessibility indicators are applied in this study, i.e., *NAL* (number of accessible locations) and *AFT* (aggregate flexible time), which are formulated as

$$NAL = \left|\{n|_{0p}^{m} | \tau(h_0, n|_{0p}^{m}) + d_a + \tau(h_1, n|_{1p}^{m}) \leq t_B\}\right| \tag{2}$$

$$AFT = \sum_{n} \max_{p} \left(t_B - \tau(h_0, n|_{0p}^{m}) - d_a - \tau(h_1, n|_{1p}^{m})\right) \tag{3}$$

where p is a parking location for the corresponding PV, and n is a location for the flexible activity.

Based on the accessibility indicators, two numeric equity metrics are used in this study, i.e., the Gini coefficient and the 20:20 ratio. Here, the Lorenz curve is a graphical analysis tool presenting the cumulative distribution of accessibility with population percentage. Gini coefficient is the numeric indicator of inequality got from the Lorenz curve ranging from 0 to 1. Consider (X_j, A_j) are the known points on the Lorenz curve with $j = 0, \ldots, m$ where m is the number of sampled points, and are ordered by the increasing values of $X_j (X_j < X_{j+1})$. X_j is the cumulated proportion of the population with $X_0 = 0$ and $X_m = 1$. A_j is the cumulated proportion of accessibility assumed by the bottom X_j of the people with $A_0 = 0$ and $A_m = 1$. 20:20 ratio is obtained by dividing the accessibility of the richest 20% population by the poorest 20% population. They are formulated respectively as:

$$G = 1 - \sum_{j=1}^{m} (X_j - X_{j-1})(A_j + A_{j-1}) \tag{4}$$

where G is the Gini coefficient using discrete points (X_j, A_j) on the Lorenz curve.

$$R_k = \frac{\bar{A}_{k\_\overline{20\%}}}{\bar{A}_{k\_\underline{20\%}}} \tag{5}$$

where R_k is the 20:20 ratio for area k, $\bar{A}_{k\_\overline{20\%}}$ is the population-weighted average accessibility for the richest 20% population, $\bar{A}_{k\_\underline{20\%}}$ is the population-weighted average accessibility for the poorest 20% population. Gini coefficient is a summarized indicator that shows accessibility distribution across the entire population that is most sensitive to the groups in the middle. 20:20 ratios can reveal the inequality between the richest and the poorest population. Combining the Gini coefficient and 20:20 ratios can provide more detailed insights into inequity than using a single indicator.

3. RESULTS

The study area covers Rotterdam, the Hauge, and their surrounding 21 municipalities (Figure 2). Over two million residents live in the study area. The road network was extracted from an open data source including 153,896 nodes and 341,522 edges with fixed average speeds for car <90, 70, 50, 30, 15>, for bike <0, 20, 18, 15, 10>, and for walking <0, 5, 5, 5, 5> in km/h at five levels of road segments. The

PT timetable of a typical workday from 10 AM to 1 PM is selected, including 416,664 basic connections with 4758 PT stops (or stations). Each basic connection records trip ID, start stop, end stop, start time, and end time between two neighboring stops.

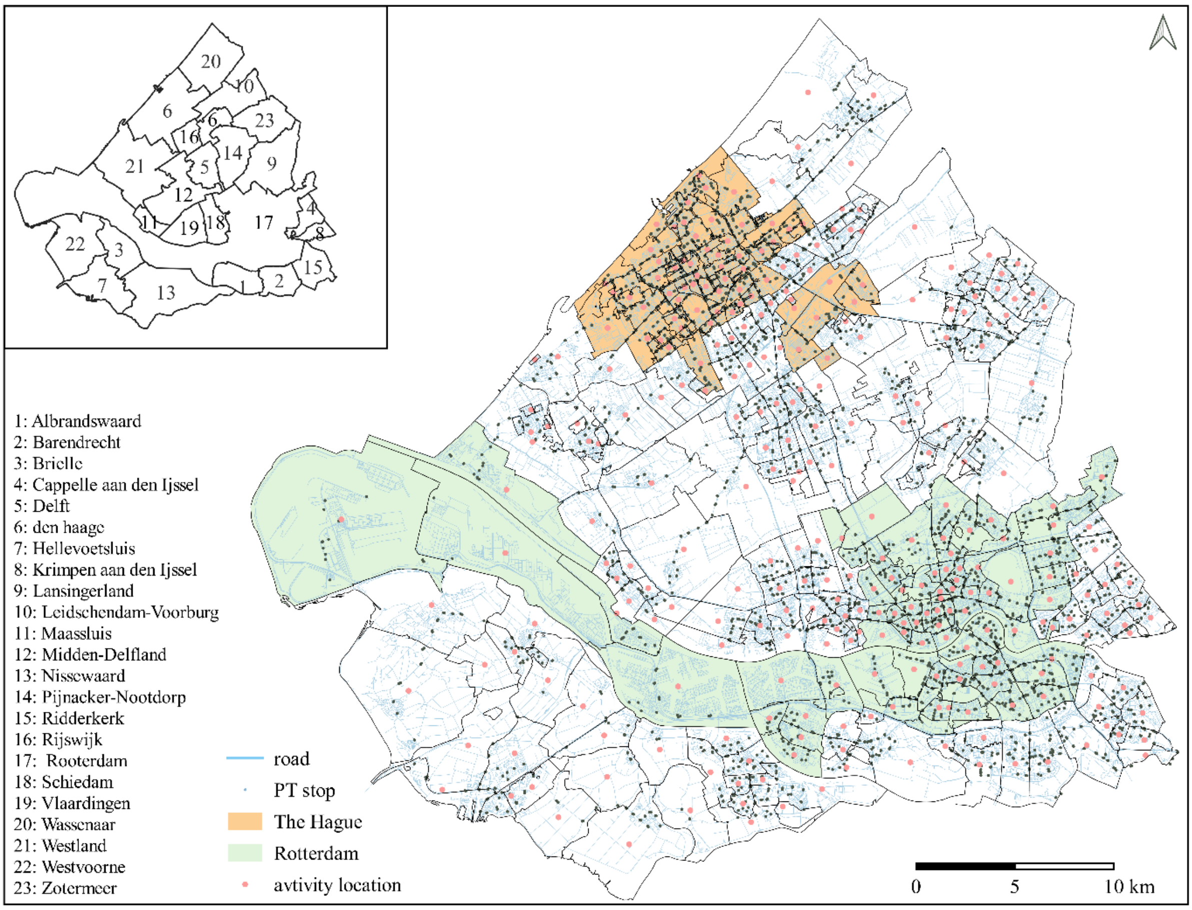
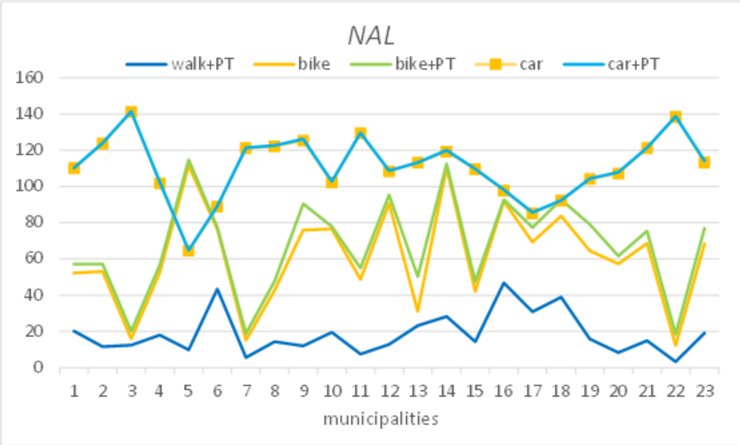


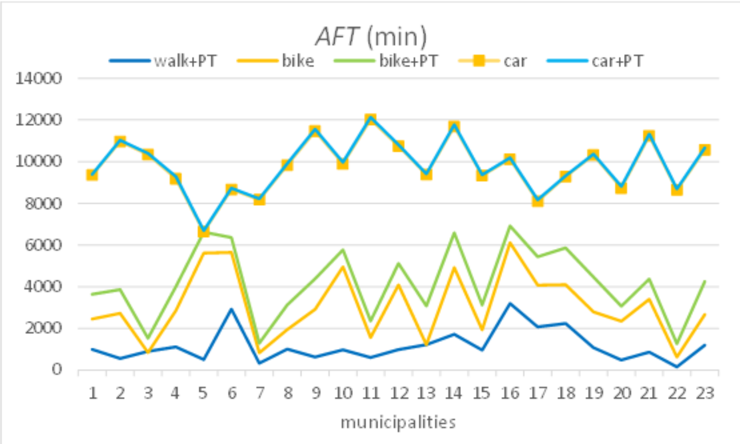
Figure 2 Study area.

Seven hundred thirty-eight locations identified from OpenStreetMap for shopping activity are unevenly distributed in the study area, and those within the same 4-digit postcode area are assumed at the geometrical center of the corresponding postcode area (Figure 2). Based on multimodal supernetwork, we measure STP-based accessibility for a sample of 23,764 individuals living in the study area according to OViN data. A fixed residential location is assigned as anchor nodes with a time budget of 3 hours and an activity duration of 45 minutes for each individual. The results and interpretations are shown below.

First, we compare the indicators *NAL* and *AFT* for each municipality using two PV only (bike and car) and three mode combinations (walk+PT, bike+PT, and car+PT). The study area covers 23 municipalities and will be ordered from 0 to 22 according to the indexes in Figure 2.



(a) *NAL*



(b) *AFT*

Figure 3 Measurements of *NAL* and *AFT*.

As shown in Figure 3, individuals who live in most municipalities have the highest accessibility when traveling by car. People owning bikes have higher accessibility than those with no PVs (i.e., walk+PT). PT positively affects accessibility both in *NAL* and *AFT* when chained with a bike, while there is no added value when chained with a car. Based on *NAL* measurement, people who live in two small municipalities (Delft and Schiedam) have higher accessibility when traveling with bike+PT compared with the car. The results show Delft is a place friendly for the bike, as it has higher *NAL* and equal *AFT* accessibility than using the car.

Second, we conducted a t-test comparing people with and without a car based on the maximum accessibility among the five modes and mode combinations. Both p values for *NAL* and *AFT* are less than 0.001, showing that owning a car in the study area, in general, represents a significantly higher level of accessibility.

Third, we calculate the Gini coefficient of *NAL* and *AFT* of five transportation modes and mode combinations (Table 1). While walk+PT has the highest Gini coefficients, the smaller Gini coefficients based on PVs show that PVs reduce the differences caused by the spatial separations. Gini coefficients based on the maximum accessibility show the level of inequality distribution of people's potential in moving. As the Gini coefficient based on maximum *NAL* and *AFT* are both less than the Gini coefficients obtained by cars, it can be concluded that multimodal transportation reduces the differences in accessibility disparity caused by car ownership.

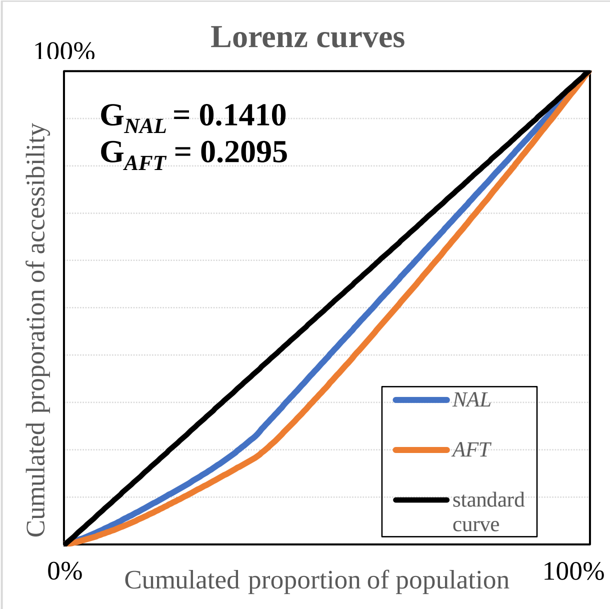


Figure 4 Lorenz curves based on maximum accessibility.

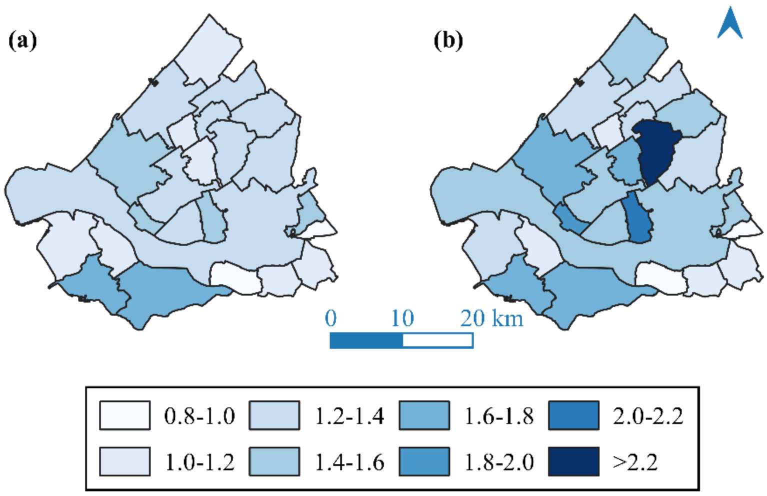


Figure 5 20:20 ratios based on maximum accessibility (a) *NAL* (b) *AFT*.

Table 1 Gini coefficients.

	walk+PT	bike	bike+PT	Car	Car+PT	Max,
Gini coefficient (*NAL*)	0.3735	0.1633	0.1528	0.3615	0.3603	0.1410
Gini coefficient (*AFT*)	0.4324	0.2230	0.1668	0.3909	0.3908	0.2095

Fourth, we calculate the 20:20 ratios as a complementary metric of Gini coefficients showing the unequal distribution of accessibility between the richest 20% population and the poorest 20% population of each municipality. The value of 20:20 ratio less than 1 means the poorest 20% of these areas have higher accessibility than the richest 20%, vice-versa. As shown in Figure 5(a) and (b), the 20:20 ratios of most municipalities fall between 1.0 to 2.2, meaning that the richest 20%, in general, have higher shopping accessibility over the poorest 20%. Nevertheless, the range of 20:20 ratios indicates that the gaps between the richest 20% and poorest 20% living in the same areas are small. Particularly, since the poorest 20% in Pijnacker-Nootdorp has no cars according to OViN data, this municipality has its largest gap between the richest 20% and poorest 20%. The ranges obtained from five modes and mode combinations separately fall into 1.0 to 5.90 without considering those poorest groups with zero accessibility. It can be concluded that multimodal trip chaining helps shrink the gaps between the richest 20% and the poorest 20% in the same area.

4. CONCLUSIONS

This study focuses on measuring space-time accessibility and equity based on STP modeling in a large-scale multimodal transportation network. We find that multimodal transportation positively affects accessibility improvements and inequity reductions. The results offer insights into urban and transportation planning and a tool for accessibility and equity measurement. Nevertheless, there are several interesting directions for the STP-based accessibility measures and equity evaluations, such as considering the dynamic travel time and monetary costs, which we will address in future works.

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