Integrated Travel Demand and Accessibility Model to Examine the Impact of New Infrastructures Using Travel Behavior Responses

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Abstract

The study aims to propose an integrated travel demand and accessibility model to examine the impact of new infrastructures on accessibility for households and employment. The cumulative opportunity measure and the space–time accessibility measure are used to describe region accessibility layout. And a zonal accessibility measure is proposed to measure attractiveness of the Central Business District (CBD). Further, accessibility measures are obtained by various transportation modes and times of day considering travel behavior and network traffic congestion.

The complete methodology is demonstrated using Maryland in the United States as a case study. Maryland Statewide Transportation Model is used to build an integrated travel demand and accessibility model. The investment in different projects for Constrained Long Range Plan (CLRP, known as the vision for future growth) is compared to a case in which there is no transportation improvement but still has the same growth. Analysis results show that (1) due to lack of transit facilities, car accessibility is much higher than transit, during peak hours; (2) because of traffic congestion, car accessibility is much lower during peak hours than off-peak hours, while transit is the opposite due to high frequency service during peak hours; (3) transit facility improvement can not only increase accessibility but also narrow the gap in accessibility during peak and off-peak hours; (4) the affected region of accessibility is primarily concentrated in the metropolitan area. Results of the study show the necessity of a multi-measure accessibility analysis to fully assess the effect of planned transportation improvements on regional accessibility.

Keywords: Accessibility; Travel demand; Activity; Traffic congestion; Travel behavior; Transit.

Introduction

Traditionally, speed and travel times are considered as important indicators of a well-functioning transportation system. Over the years, characteristics such as the system reliability, vehicle miles of travel, vehicle hours of travel and accessibility have gained importance in practice when evaluating system performance. Admittedly, capacity and arrangement of transport infrastructure are key elements in determining accessibility(Rodrigue, Comtois, and Slack 2016), and different travel behaviors (including the destination choice, mode choice, etc.) contribute to different accessibility. The concept of accessibility focuses on quantifying the availability of opportunities generated as a result of both transportation supply and land use characteristics. Transportation accessibility is one of the principal outcomes of a transportation network performance and the geographical distribution of activities(Páez, Scott, and Morency 2012). On the other hand, accessibility influences the organization and the dynamics of regions and, consequently, the location of activities and individual's location choices. Thus, transportation accessibility plays a crucial role in land use development, travel behavior and traffic patterns of a region. Therefore, quantification of accessibility provides planners and policy makers with an invaluable tool to guide capital investments and policy decisions.

It is imperative that improving accessibility through strategies such as improving transit facilities will help alleviate traffic congestion(Schrank, Lomax, and Turner 2010). These improvements are represented generally in the Constrained Long Range Plan (CLRP) of the USA. CLRP is the blueprint to build future transportation infrastructure to accommodate future land use growth, which includes proposed new highway and transit improvements. Regionally significant projects and programs in CLRP seek to facilitate the efficient movement of people and goods using a variety of transportation modes(Metropolitan Washington Council of Governments, 2018). The concentration of this paper is to evaluate the accessibility impacts that new investments will result in because of additional supply and induced demand. The impacts of transportation system development in CLRP are compared to a case in which there is no transportation improvement but still has the same growth (No-build).

Often accessibility is estimated using travel time, distance or cost, rarely taking traffic congestion effect into account, especially in urbanization developments (Morris, Dumble, and Wigan 1979). Christodoulou et al. pointed out that different traffic conditions especially traffic congestion strongly influence accessibility(Christodoulou et al. 2020). Future traffic congestion is strongly associated with socio-economic, demographic, trip generation, destination choice, mode choice, and route choice characteristics. Without a functional travel demand model, it is nearly impossible to assess true impact of accessibility in the future. A tool of such type has multifaceted advantages. First, to analyze the reallocation of activities and improvements of accessibility. Second, to obtain the outcome stemming from changes in mobility plans of transportation and unbalanced accessibility, which may influence additional social equity and productivity. Third, to reallocate land use and transportation for an efficient transportation system. It is indeed an integrated travel demand and accessibility tool that can be highly valuable to transportation planning, which is proposed in this paper.

The structure of the paper is as follows. First, a brief review of relevant work in the literature is given. Second, the methodology and the joint travel demand models are described. Then, the study area and the data of the case study are showed. Next, the results are discussed, and comparison of main indicators is presented. Conclusions and interesting findings are reported in the final section.

Literature Review

Accessibility and Related Factors

Early accessibility literature focused on the potential of opportunities for interaction(Hansen 1959); followed by the measure of the ease of reaching land-use activities from a location using a specific transportation mode(Dalvi, M.Q.; Martin 1976); and most recently the extent to which land-use and transportation systems enable (groups of) individuals to reach activities or destinations by a (combination of) transportation mode(s) (Geurs and Ritsema van Eck 2001). One of four main components are typically identified by accessibility measures, which are land-use, the transportation system (infrastructure based), temporal impacts and individual traveler characteristics (Götschi et al. 2017; Edelenbosch et al. 2017; Tang et al. 2018; Ye et al. 2018; Zou et al. 2018). This paper focuses on transportation infrastructure to measure access to specific land uses, defining accessibility as the number of accessible households and employment opportunities via a specific transportation mode within a given amount of time. We add to the existing literature by incorporating traffic congestion, travel time by multiple transportation modes and the impacts of future transportation investments.

Effect of Travel Mode

Car accessibility can be computed using mapping/ illustrations or model data, which is to evaluate the highway network (Loustau et al. 2010) or urban structure(Shen 2006). Similarly, accessibility by transit facilities has been explored to analyze the transit system (Bertolaccini, Lownes, and Mamun 2018) and examine the connection of transit accessibility to others such as transit ridership(Chow et al. 2006) in the past by similar methods. In terms of the effect of travel mode, it has been demonstrated that mode choice affects the employment participation (Alam 2009), but generally travel behavior computation in accessibility to examine the impact of new infrastructures is rare.

Effect of Time of Day

Because the availability of opportunities is different at different time of day, especially during the traffic congestion, so the time factor is important when measuring accessibility, which has been mentioned by some researchers(Christodoulou et al. 2020; Zou et al. 2017).Therefore, the impact of time was analyzed (Delafontaine et al. 2011) and accessibility was compared by time of day (Christodoulou et al. 2020) among the few studies, which will also be taken into key consideration in this paper through detailed travel time and speed in peak and off-peak hours.

Other Methods of Accessibility

Basic data is critical for accessibility analysis to obtain related parameters, and it can strongly influence the results. There are several ways to get data: (1) survey data such as floating vehicle data to obtain speed or travel time, and further to obtain real-time accessibility(Li et al. 2011); (2) construct a topological graph including nodes and arcs (roads), and each arc is characterized by a length and a design speed which is used to calculate the travel time on the road network(Odoki, Kerali, and Santorini 2011); (3) develop some geo-computational methods or tools based on GIS (Mavoa et al. 2012; Liu and Zhu 2004); (4) apply transportation models such travel demand models to get distance and travel time(Levinson 1998). Various methods are selected due to different targets and indicators. Our tool is based on the fourth type of method, which has comprehensive data and is suitable for a wider range of road network.

In general, the literature suggests that travel behavior computation in accessibility and demonstration of results is limited. The objective of this paper is to analyze the spatial disparity through several accessibility indicators and to compare transit versus car as well as peak versus off-peak accessibility under both CLRP versus No-build scenario. The aim is not only to identify the local disequilibrium, but also to reveal the impact on transportation accessibility by travel mode, time of day, improvement options. Based on various typologies of accessibility, measures are proposed to assist the decision-making of planners and policy makers.

Methodology

The methodology section is organized into three sections. First, a description on traditional accessibility is presented. Then, travel cost computation and travel time estimation to a zone from neighboring zones is presented. Finally, a complete description of an integrated travel demand and accessibility model is discussed.

Measuring Accessibility to Jobs

A location-based accessibility measure is utilized in the paper describing spatially distributed activities, specifically the number of jobs within a given travel time period from the origin to locations at the destination.

Cumulative opportunities are often used to measure transport accessibility, and the general formulation is as follow(Koenig 1980):

$$A_{ijk}^{m} = \sum_{j} \left(g(O_{jk}) \cdot f_1(c_{ij}^{m}) \right) \tag{1}$$

A_{ijk}^{m} is the accessibility from the origin zone (traffic analysis zone) i, to opportunities of type k in destination zone j, for the travel mode m; and $g(O_{jk})$ is a function of opportunities of type k at location j, while $f_1(c_{ij}^{m})$ is the function of generalized travel cost indicator between i and j as perceived/experienced by travel mode m(Levinson 1998).

For two modes (car and transit), $g(O_{jk})$ is equal to the total jobs in zone j. As for $f_1(c_{ij}^{m})$, we use the travel time as travel cost function as follows:

$$f_1(c_{ij}^{m}) = \begin{cases} 1, if\ t_{ij}^{m} \le t_h \\ 0, if\ t_{ij}^{m} > t_h \end{cases} \tag{2}$$

Where t_{ij}^{m} is the travel time from zone i to zone j by mode m, and t_h is the threshold travel time. It should be noted that t_h is a constant and its value is determined according to the needs of researchers, which is 30 minutes in this paper. Further, to determine accessibility by different time periods of the day following equation can be used.

$$f_1(c_{ij}^{m}) = \begin{cases} 1, if\ t_{ij}^{m,p} \le t_h \\ 0, if\ t_{ij}^{m,p} > t_h \end{cases} \tag{3}$$

Where, p is the time of day.

Travel Cost by Mode

Primarily two major modes: car and transit are considered. Travel cost by car can be represented as the following

$$t_{ij}^{a} = t_{ij}^{0} + \frac{\tau}{\rho} + \alpha \cdot t_{ij}^{0} \cdot (\frac{q}{c})^{\beta} \tag{4}$$

Where, t_{ij}^{a} is the composite travel time between origin i and destination j by car in seconds, t_{ij}^{0} is the corresponding free flow travel time in seconds, τ is the toll value in cents, ρ is the value of time in cents/second which depends on the income (Costinett et al. 2009), q is the traffic volume, c is the capacity, and α, β are the parameters which are 0.15 and 4 respectively. The travel cost function is a revised BPR impedance function (Transportation Research Board 2000).

In this paper, we use congested time during different time periods of day instead of using the design speed or average speed, so the results will be more realistic. We obtain t_{ij}^{m} (the congested travel time by car or transit during different time of day) through the statewide travel demand model (Y. Wang et al. 2016), which will be described later.

For transit links, eight modes are considered: four by walk and four by drive. Four walk modes consist of walk to rail, walk to commuter rail, walk to bus, and walk to express bus. Similarly, four drive modes are drive to rail, drive to commuter rail, drive to bus, and drive to express bus. Non-transit links are created that connect Transit services to the Highway links. A non-transit leg is an imaginary entity representing a link (or series of links) required to establish the connection between transit and highway. The costs, such as distance and time, needed to traverse the leg are derived from the sum of the links traversed. In Fig. 1, roadway and non-transit links are combined into the following links for non-transit modes. In real world, transit access and egress links have horizontal and vertical curvatures following real world topography. But for simplification purposes, straight line distances are used for computation in this paper. Fig. 1 shows that how walking and driving to bus and rail are determined in the model. Following are the formula used for computation of distances.

Walk to Rail = $C_1 + L_1 + W_1$

Walk to Bus= $C_1 + L_1 + L_2$

Drive to Rail= $C_1 + L_1 + D_1 + W_3$

Drive to Bus= $C_1 + L_1 + D_1 + W_2 + L_2$

where,

C_1: Distance from the centroid connector to the node

L_1: Distance from highway node N_1 to N_2 (that is closer to the transit station)

W_1: Walking distance from the highway node to the rail stop if the mode is walk to rail

L_2: Walking distance from the highway node to the bus stop if the mode is walk to bus

D_1: Driving distance from highway node to Parking and Ride (PnR) Lot

W_3: Walking distance from the PnR Lot to the rail stop if the mode is drive to rail

W_2: Walking distance from the PnR Lot to the bus stop if the mode is drive to bus

Walk to transit

Fig. 1(a). shows that a trip is originated from the centroid of the zone and traverse a distance C_1 from the centroid connector to the nearest node; then it searches for the nearest node close to a transit stop. L_1 represents the distance from the first node (connecting centroid) to the nearest node closer to a transit stop. The final segment of the walk trip is made by walk to a rail stop (W_1), or to a bus stop (L_2).

Drive to transit

Similar to walk mode, C_1 and L_1 are also first two components of the access for drive. The third components of the drive are to that of PnR denoted as D_1 in Fig. 1(a). If the destination is a rail stop, W_3 is the last segment describing walking distance from the PnR to the rail stop. If the destination is a bus stop, W_2 represents the walking distance from the PnR station to a highway node (N_2), and then the distance from the highway node to the bus stop (L_2) should be traversed. Fig. 1(b). suggests that a straight line is geographically created to reflect the sum of all the components shown in Fig. 1 (a). The use of straight-line distance in the mode is twofold: (1) To make computation easier, (2) also for plotting about transit access and egress links.

Measuring Travel Time Accessibility to CBD

This paper proposes accessibility measures to Central Business District (CBD) because it represents the destination with higher share of market/service in the study area. We propose space–time accessibility measure and multiple cumulative opportunities. The space–time accessibility measure can estimate the service level of transportation infrastructure, such as the level of traffic congestion of the network, which is formulated using map algebra concept as follows(Koenig 1980):

$$A_{ij}^{m} = f_2\left(c_{ij}^{m}\right) \tag{5}$$

A_{ij}^{m} is the accessibility from the standpoint of origin zone i to zone *j*, from the perspective of travel mode *m*; And $f_2\left(c_{ij}^{m}\right)$ is the function of generalized travel cost between *i* and *j* as perceived/experienced by travel mode *m*. Here we use the travel time as travel cost as follow:

$$f_2\left(c_{ij}^{m}\right) = t_{ij}^{m,p} \tag{6}$$

Where $t_{ij}^{m,p}$ is the travel time from zone i to zone *j* by mode m during the time of day *p*. The travel time calculation also considers congested time as shown in equation-4. Therefore, equation-5 means the spatial range that can be reached within $t_{ij}^{m,p}$.

Accessibility Computation in Travel Demand Model

A travel demand model is very suitable for computing multiple components of accessibility such as effects during (1) various times of day, (2) selected mode, (3) jobs attracted, and (4) travel time needed to reach a CBD. This section describes how an accessibility model is developed and the algorithmic steps of the process embedded into a typical four-step travel demand model process.

The algorithm process steps are shown in Fig. 2. The model takes traffic congestion into consideration and provide feedback according to travel behavior response.

The procedure for obtaining best journey time for transit is shown in Fig. 3. Best journey time is the minimum travel cost for transit through eight modes of transit: (1) rail, (2) commuter rail, (3) bus, (4) express bus, cross classified by drive and walk. Travel cost is determined as the shown in Fig. 3. For each mode, the shortest path is determined using the multimodal network, fare of each transit mode, and value of travel time for various income categories.

Data

Data obtained from various sources are described below.

Land Use Data

Household and employment data from Department of Transportation (DOT) of Maryland (MD) is collected. The DOTs provided base year (2007), and future year (2030) data at traffic analysis zone (TAZ) level.

Network

A multi-modal network at the statewide level includes highway and transit networks which are prepared in the following ways.

Highway Network

The highway network and associated link attributes data were compiled from various existing models, including Metropolitan Planning Organizations (MPO), DOTs, and other sources, and standardized. Network reconciliation includes the re-numbering of nodes to establish unique values for modeling processing. Several sources were used to develop an initial set of network attributes for the MSTM.

Transit Network

The transit network data was available from various MPOs. Eight modes of transit: (1) Local Bus, (2) Express Bus, (3) Premium Bus, (4) Light Rail, (5) Metro Rail, (6) Commuter Rail, (7) Amtrak Rail, (8) Greyhound bus. Park-N-Ride (PnR) node information was extracted from the MPO model files, and then those nodes were re-numbered and added to the master network. PnR lots serve some specific stations which have to be coded along with the PnR information during the model run to facilitate the generation of Zonal Drive access legs. Transit fare, route, schedule, operating speed and frequency are used to prepare the master transit network. In the end, the master network consists of merger highway and transit network, as some transit modes share the guide way with highway network, while some have fixed guide ways.

Travel Time

Zone to zone travel times are often referred as skims or skim matrices. The following paragraphs explain how highway and transit skims are developed.

Highway Skim

Zone to zone distance, travel time and tolls are needed to compute the highway skim. Please refer to equation (4) for obtaining the travel cost formulae. Intrazonal travel times and distances are assumed to be 60% of the average of nearest three zones. Terminal times, assumed to be a function of area-type of a zone, are also added to the skims for both origin and destination zone. Skimming is done for peak as well as off-peak periods of the network.

Transit Skim

Prior to skimming, non-transit legs are added to the transportation network. A non-transit leg is a representation of a bundle of walk and drive links that can be combined to form a path with the attributes such as the sum of distance, time and other parameters of the underlying network links. There are four kinds of non-transit legs: walk-access, walk-egress, car-access, and walk-transfer. There are park and ride nodes built in the network, along with the car access links and walk egress links, for those PnR nodes to the highway system. Links connecting the PnR lots to the Rail or Bus routes are also created.

Four modes are skimmed: Bus, Express Bus, Rail and Commuter Rail. In addition to these, walk and drive to all transit modes are also skimmed. Prior to skimming, the network is augmented with drive access links and walk access links to facilitate the access, egress and transfers. A variety of quantities shortest path matrices are included: initial wait times, transfer wait times, total walk time, car times, car distances (meant for car access, will be zeros for walk access), number of transfers, total bus time (including local, express and premium MTA buses), rail time (light, commuter and metro rail included), actual times on all transit modes, shortest journey times, local bus times, express bus times (would be zero when only local bus is allowed, etc.), metro and light rail times, commuter rail times, transfer and boarding penalties, times and distance of Amtrak and Greyhound modes.

Case Study

To demonstrate the proposed methodology, we used Maryland in the United States (U.S) as a case study.

Maryland consists of 23 counties, one independent city and with a total population of 5.8 million and a total employment of 3.4 million in the year 2010 (Chakraborty and Mishra 2013). The state has 17 types of public transportation systems including metro rail, commuter rail, local bus and long-distance bus. To develop our dataset, we subdivided the state into 1,151 TAZs. The TAZ development went through an iterative process including several reviews by the State Highway Administration and was part of a larger modeling project. We identified the broader study area using 2000 Census Transportation Planning Package data to encompass the bulk of labor flows in and out of Maryland. The outline of the state and the broader region with its major proposed projects are shown in Fig. 4.

Fig. 4. illustrates the three major investments proposed for the state. Features of the additional facilities are shown in Table 1. Two major transit projects namely: Red line and Purple line; and a host of Electronic Toll Lanes (ETLs) are included in the CLRP. Red Line is a proposed light rail facility in Baltimore CBD area encompassing 14.1 miles with capital investment of $1.8 billion (measured in 2010 US $). Red Line is proposed to have 15 surface and four underground stations with average estimated daily ridership of 57,000 (MTA 2018a). Purple line is a proposed metro system in Southern Maryland connecting existing Green and Yellow lines in the Washington DC area and comprising 21 stations over 16 miles in track length. Purple line is estimated to carry over 68,000 riders per day by 2030 and will require capital cost of 1.93 billion(MTA 2018b). Set of ETLs both in Baltimore and Washington DC metro area portion of Maryland are proposed as managed facility to act as high occupancy toll and/or high occupancy vehicle facilities.

The network and zone structure used for analysis is also shown in Fig. 4. The network represents highway links (interstates, major arterials, minor arterials, collectors and local roads) and transit facilities including metro rail, commuter rail, light rail, and all types of bus lines in the region. The main criteria for TAZ delineation included conforming to census geographies and nesting within Counties, separating traffic sheds of major roads, and employment activity centers, and a frequent grouping of adjacent TAZs, where they existed. According to CLRP, the variations in land use patterns across the state are characterized in Fig. 5. Both household and employment density maps show the concentrated growth in the central portion of the state by 2030, while other parts are relatively less dense.

Two scenarios are considered: (1) CLRP and (2) No-build. CLRP refers to a case where all new projects with new infrastructure will be built (see Table 1). No-build refers to a case with no new infrastructure being added in the future. New infrastructure provides new accessible links and then have an impact on the accessibility to jobs, time needed to reach a CBD, spatial location of employment and households, which are examined by comparing two scenarios. In order to analyze the impact separately, here the household and employment are assumed to remain unchanged under the two scenarios. The computational framework of proposed models is built using Cube Voyager software developed by Citilabs(Citilabs. 2018). Basic Cube Voyager GIS functionalities such as zone, node, link attributes, shortest path generation, centroid creation, etc. are used, and scripts are written for highway skim, transit skim, and accessibility computation.

Results and Discussion

The analysis results are presented in this section. First, comparison measures used for the analysis are described. Second, the results of statewide employment accessibility by time of day and mode are presented following by a detailed analysis of accessibility to Baltimore CBD. Finally, comparisons of different time of day are made and multiple accessibility measures of CBD are reported.

Two Dimensional Comparisons

A two-dimensional comparison is conducted. Scenario results can be analyzed in two ways. For example, for scenarios CLRP or No-build, comparison can be done first, relating accessibility effects during different time of day and by different modes. Second, it can be done by relating measures between scenarios. Each type of comparison is discussed in the following sections for two scenarios (CLRP, No-build), and two performance measures (number of jobs, travel time) and by two control variables (time of day, mode).

Car Accessibility by Time of Day

Car accessibility by CLRP and No-build is shown in Fig. 6. In Fig. 6(a). and 6(b)., maximum number of jobs accessible to each zone in a 30-minute commute is shown for CLRP. Similarly, in Fig. 6(c). and 6(d). job accessibility for No-build scenario is presented. In comparison within scenarios, it is observed that for CLRP, the number of accessible jobs is less during peak hours than off-peak hours. Because of traffic congestion, travel time to access each zone increases during peak hours, while for off-peak hours more jobs can be accessible because of less traffic congestion (Fig.6(a)., and 6(b).). More jobs are accessible to Baltimore CBD and the southern Maryland which is suburbs to Washington DC. Similar effects are also seen for the No-build scenario. For comparison between scenarios, it is seen that more jobs are accessible for CLRP. This is justified as more infrastructures provide greater accessibility. Irrespective of comparisons within and between scenarios, western and eastern parts of the state are still rural areas with little accessibility.

Transit Accessibility by Time of Day

Transit accessibility by time of day for CLRP and No-build is presented in Fig. 7. And 30-minute transit accessibility by peak and off-peak hour for CLRP is shown in Fig. 7(a). and 7(b). respectively. Similar figures for No-build scenario are presented in Fig. 7(c). and 7(d). In comparison within scenarios, peak hour transit accessibility is a little higher than off-peak hour because of the fact that the frequency of transit service is a little higher during peak hour. Number of jobs accessible by transit in a 30-minute commute is much less than by car because of limited transit access to the suburban and rural areas in the state. In comparison between scenarios, it is observed that CLRP has a little higher transit accessibility compared to No-build in local areas because only two transit lines were added. The effect of transit lines (redline and purple line) is noticeable. The eastern and western parts of the state are mostly rural with little or no transit accessibility.

Car Accessibility to CBD

Zone 64 is considered as the CBD as it resulted with highest car and transit accessibility. Accessibility to CBD is computed using equation (5) and (6). Fig. 8(a). and 8(b). show travel time required to reach CBD for CLRP scenario for peak and off-peak hours by car. Similar corresponding results are presented for No-build scenario in Fig. 8(c). and 8(d). In comparison within scenarios, it observed that more zones are accessible during off-peak period for CLRP. This is because during off-peak hours highway is less congested and thus CBD is more accessible. In comparison between scenarios, more zones are accessible to CBD in CLRP scenario compared to No-build.

Transit Accessibility to CBD

Transit accessibility to CBD is computed using equation (5) and (6). Fig. 9(a). and 9(b). show travel time required to reach CBD for CLRP scenario during peak and off-peak periods by transit. Similar corresponding results are presented for No-build condition in Fig. 9(c). and 9(d). In comparison within scenarios, it can be seen that more zones are accessible during peak period for CLRP. This is because the level of service is high during peak hours and thus CBD is more accessible. In comparison between scenarios, more zones are accessible to CBD for CLRP case as compared to No-build due to new infrastructure.

Overall Peak and Off-peak Hour Accessibility

In Fig. 10., travel time comparison during peak and off-peak period for CLRP and No-build is presented. Each data point represents travel time from each zone to CBD during peak (x-axis) and off-peak (y-axis) hours. Each sub-figure in Fig. 10. a dotted line (representing 45 degree of slope), and the best linear fit (solid line) is shown. In addition, a linear equation and the corresponding r-square are also shown in each graph. Following description shows observation from Fig. 10.:

Comparison within scenarios

- If *Y=rX* and *r>1* which means y-axis value is more than x-axis value. For example, in Fig. 10(a). *Y = 1.132X*, it means it requires more time to travel during peak hours than off-peak hours for car mode. (Please note that *Y=rX* is a functional form given here as an example)
- If *Y=rX* and *r<1* which means y-axis value is less than x-axis value. For example, in Fig. 10(b). *Y= 0.9731X*, it means it requires less time to travel during peak hours than off-peak hours for transit mode

Comparison between scenarios

- For *r>1*; *Y = 1.132X* for Fig.10(a)., and *Y = 1.18X* for Fig. 10(c). which means the rate 1.13<1.18 which means the No-build case is more congested compared to CLRP.
- For *r<1*; *Y = 0.9731X* for Fig. 10(b)., and *Y = 0.8943X* for Fig. 10(d). which means the rate 0.9731>0.8943 which suggests that transit is more accessible in CLRP than No-build.

Fig. 10. shows that irrespective of location of any zone, car has best accessibility compared to transit for CLRP. Similar observation is for car for No-build. But CLRP for all cases has better accessibility compared to No-build. The graphs demonstrate intuitive expectations for CLRP and on the same token shows loss in travel time for No-build scenario.

Combined Household and Employment Accessibility

A new perspective on available household and employment (or referred as job here) of Baltimore for CLRP and No-build is presented in Table 2(a), and 2(b) respectively. The result shows that for 30-minute travel time there are 660,000 households and 1,202,000 jobs accessible to CBD for CLPR, which results in a job housing balance (JHB) of 1.7. It shows that a number of houses can be built in these areas for a better JHB. As comparison within scenarios for 30-minute time, accessible jobs are more to CBD in off-peak hours and the corresponding JHB is higher. The purpose of estimating JHB is to assess how many more housing units can be constructed to have access to number of jobs in a time frame (say 0-30 minutes). For comparison within scenarios, it is evident that more jobs are accessible by highway than transit. In comparison between scenarios, CLRP has more accessible jobs in a time frame than No-build.

Conclusion

Accessibility can be used to evaluate transportation policies and are particularly useful when consider multiple aspects related to urban structure, transport system quality, and infrastructure investment. The number of accessible employment opportunities to reach destinations gives an idea of the impacts resulted from transportation projects when considering accessibility. Accessibility computation should base on detailed travel conditions instead of assumed (or average) speed and travel times. Accessibility to jobs and housing can shift dramatically between travel periods, affecting individual accessibility by affecting travel behavior in destination, mode and route choice.

An integrated accessibility and travel demand methodology is proposed in this paper. The methodology is applied to estimate attractiveness of zones by time of day and mode in terms of employment and travel time. Two scenarios are developed namely CLRP and No-build. The effect of three major facilities of CLRP is examined here: Purple Line, Red Line, and Electronic Toll Roads in Maryland.

The accessibility estimates are examined using comparisons within and between scenarios. Comparisons within and between scenarios are made for employment accessibility by different modes and time of day by a threshold time interval. Further, time to CBD by car and transit is discussed. The proposed methodology can be used as a tool in the investment decision making processes to examine the impact of different transportation facilities.

A case study within the Maryland provides new insights into accessibility impacts stemming from a variety of potential transportation investments. From the case study, we find useful conclusions for accessibility. Comparisons within scenarios inform us the impact of travel mode and time of day. First, travel mode has a significant impact on accessibility: car accessibility is always much higher than transit. Second, time-of-day has a different effect on car and transit: car accessibility is much lower during peak hours because of traffic congestion, while transit is more accessible during peak hours due to higher frequency vehicle service. Comparisons between scenarios primarily show the impact of facilities improvement. Improving transit facilities makes transit more accessible and attractive. Meanwhile, it can also reduce traffic congestion and increase car accessibility. From combined comparisons within and between scenarios, we find that facility improvement can not only increase accessibility but also narrow the gap of accessibility and travel delay between peak hours and off-peak hours. In addition, combined household and employment accessibility, jobs can access more to CBD in 30-minute time and the corresponding JHB is higher especially by transit.

This paper contributes to transportation planning and decision-making practice by defining two accessibility measures as policy guidance and investment decision tool to analyze the impacts of new facilities, which can be obtained by travel demand models. The contribution of the paper is threefold. First, we propose a methodology demonstrating accessibility measure integrating with a travel demand model. Second, we show the significance of comparisons within and between scenarios. Third, we demonstrate the methodology with the help of a case study. We acknowledge that there is room for substantial improvement in the scope of application of the proposed approach. In the future, the complete modeling approach can be developed based on activity travel demand models rather than trip-based models and the complete process can be integrated in a full GIS-based environment. Another future task can be done to extend the models and the process can include walk and bike modes and associated accessibilities. Besides, a deep comparison of different scenarios should be done considering the interaction between accessibility and household and employment location.

Data Availability Statements

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g. anonymized data). The funding agency does not allow the data to be open to the public without their permission.

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