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The determinants of travel demand between rail stations: A direct transit demand model using multilevel analysis for the Washington D.C. Metrorail system

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ABSTRACT

Transit demand models have become indispensable tools for transit planners and mangers in the 21st century. By quantifying the relationship between transit ridership, the cost of travel, the character of the built environment, and the socio-economic characteristics of riders, such models enable transit planners and managers to make more informed decisions regarding transit routes, levels of service, transit fares, transit oriented development (TOD) and other transit supply parameters. Direct ridership models (DRMs) are now able to address transit ridership at each station directly with higher sensitivity to built environmental characteristics in well-defined station areas. More recently Origin-Destination DRMs have begun to use data on ridership between each origin and destination pair to facilitate more precise estimation of transit demand by origin-destination pair.

In this study, we developed a time-of-day Origin-Destination Direct Transit Demand Model (OD-DTDM) that uses fare-card data from the Washington DC Metrorail system, applying a multilevel (or hierarchical) model to address the statistical problem due to the presence of groups or clusters of observations. We examine the research questions: (1) what are the determinants of transit demand between *the origin and destination stations* in the DC Metrorail system *by time of day?* and (2) what are the magnitudes of impacts that land use factors, as well as factors of fares and travel time of other modes, have on transit demand vary *by time of day*? To address statistical complexities introduced by the fact that each station represents both an origin and a destination, we applied multilevel (or hierarchical) modeling techniques. Using these techniques, we found that the number of households and the number of jobs within a walkshed serve as trip generating and attracting factors, respectively, in the AM peak period, but with higher positive coefficients for jobs; these two factors reverse their roles in the PM peak period. Other variables with substantial effects on ridership include transit fares per mile, travel time between OD-stations by car and by bus, parking capacity, the level of feeder bus service, and train service levels. While these findings are not surprising, the time-of-day OD-DTDM provides more detailed information regarding the determinants of transit demand with temporal variation, and enables transit planners and managers to adopt policies and plans, such as transit oriented development, fare structure, and service levels, more fine-tuned for each origin and destination pair and by time of day.

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1. Introduction

Transit demand models have become indispensable tools for transit planners and mangers in the 21st century. By quantifying the relationship between transit ridership, the cost of travel, the character of the built environment, and the socio-economic characteristics of riders, such models enable transit planners and managers to make more informed decisions regarding transit routes, levels of service, fares, transit oriented development (TOD) and other transit supply parameters. Direct ridership models (DRMs) that have been developed in the transit research and practice in the last two decades provide a useful tool for transit planners to estimate transit ridership at each station directly with higher sensitivity to built environmental characteristics in well-defined station areas, as well as transit service levels and demographic characteristics of residents. These types of models highlight the importance of TOD and TOD-related policies even though transit operators are not typically able to facilitate TOD themselves.

In this study, we developed a time-of-day Origin-Destination (OD) Direct Transit Demand Model (DTDM), applying a multilevel (or hierarchical) model to address the statistical problem due to the presence of groups or clusters of observations. We addressed two main questions: (1) what are the determinants of transit demand between *the origin and destination stations* in the Washington Metropolitan Area Transit Authority (WMATA) Metrorail system *by time of day?* and (2) what are the magnitudes of impacts that land use factors, as well as factors of fares and travel time of other modes, have on transit demand vary *by time of day*? We use the term "direct transit demand model (DTDM)," because our models use passenger miles traveled (PMT), instead of ridership, as a measure of transit demand, intending that this DTDM is a broader term inclusive of DRM. This OD-based approach is more advanced than many of the previous DRMs, as it takes into account the directional peaking in transit demand by time of day and allows us to gauge the net effects of influential factors on ridership by time of day, clearly distinguishing trip generating factors, trip attracting factors, and those that affect both. The capacity to handle the temporal variation in transit demand modeling is important because the temporal and associated directional peaking in demand substantially affects not only ridership and fare revenue but also the supply level of service and associated costs (Cervero, 1982; Savage, 1988; 1989; Taylor et al., 2000). Another advantage of the OD-based approach is the ability to include trip-based characteristics, such transit fares, travel distances, and travel times by mode, as explanatory variables to examine their influence on transit demand. Especially, the effect of fares on transit demand—that is, transit fare elasticity, which can also vary by time of day—is critical for transit agencies because transit fares affect transit ridership and fare-box revenues. This development of our OD-DTDM was made possible by the data collected from WMATA's smart fare-cards (SmarTrip) that include information on trip origin and destination stations, time of travel, fare-payments, and more.

The remainder of the paper is organized as follows. The next section provides a review of studies on DRMs that analyze the determinants of transit ridership and their relative effects. Section 3 describes the context of our study area, and Section 4 describes the data and data sources. Section 5 explains the analytical approaches we apply. In particular, we explain the multilevel (or hierarchical) modeling method that addresses statistical complications arising from the use of OD-station pairs as the unit of analysis, as well as two other important dimensions of our OD-DTDM. Section 6 presents our results and a discussion of our findings. We conclude with a discussion of how our results can be used to enhance transit planning and management, and offer suggestions for future research.

2. Literature review

While the literature on Direct Demand Models has evolved since the late 1960s, its applications took somewhat different paths in the engineering and planning fields. The applications in the engineering field are traced back to late 1960s (Ortúzar and Willumsen, 2001). Direct demand models integrate trip generation, trip distribution and mode split embedded in four-step models into one formula with a wide range of explanatory variables, such as attributes of competing modes, level of service, and activity variables at trip origins and destinations (Ortúzar and Willumsen, 2001). The earliest models were in the multiplicative form of equation that estimated demand as a function of demographic variables, such as population (P) and income (I), in each zone (*i* and *j*), and travel attributes of modes (*k*), such as (*t*) and cost (*c*), for each zone pair. The initial formula was revised in the reduced form organized by attributes of origin-zone, of destination zone, and of travel mode (Manheim, 1979):

$$T_{ijk} = \varphi(P_i^{\theta_{k1}} I_i^{\theta_{k2}})(P_j^{\theta_{k1}} I_j^{\theta_{k2}}) \prod_{m=1}^{M} L_{ijm} \tag{1}$$

$$L_{ijm} = (t_{ij}^{m})^{\propto_{km}^{1}}(c_{ij}^{m})^{\propto_{km}^{2}} \tag{2}$$

where φ is a scale parameter for different trip purposes. θ_{k1} and θ_{k2} are demand elasticities with respect to population and income; and $\alpha^1{}_{km}$ and $\alpha^2{}_{km}$ are demand elasticities with respect to time and cost of traveling. M is the total number of modes considered.

Recent applications of direct demand models have been developed for high-speed rail and air transportation with a focus substantially on *inter-city* travel flows (Albalate and Bel, 2012; Campos and de Rus, 2009; Clewlow et al., 2014; Givoni, 2006; Lin and Chen, 2003) but less on *intra-city* transit travel demand. There are, however, a few exceptions: Talvitie (1973) developed a direct travel demand model for bus and rail modes using work trip data between analysis-unit zones in the Chicago central business district, using Constrained Least Square (CLS). Thompson (1997) deployed a Poisson regression-based direct demand model to identify the trip production and attraction factors associated with transit travel demand between analysis-unit zones in Sacramento, California, and found that the increasing commuting time by car on highways led to the higher transit trips. Kepaptsoglou et al. (2017) used both traffic demand data and stated-preference information collected from a survey to develop a direct demand model at the zone-to-zone