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High-resolution spatio-temporal modeling of public transit accessibility

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A B S T R A C T

This paper details the creation of a model to measure the accessibility, in the form of travel time, from origins to destinations by way of public transit. The model is a high-resolution spatio-temporal, GIS-based public transit network model. It includes the travel modes of walking and bus and their associated travel times. The total travel time is based on walking times to reach bus stops, typical waiting times at bus stops, travel times on the bus network and transfer times between routes, if necessary. As an example of the model's applicability, it is used to analyze the effects on accessibility of the addition of rapid bus routes in Albuquerque, New Mexico. This multimodal, network-based model has other applications as well, such as assessing sustainable transportation performance measures, estimating transit demand based on varying value of time, or comparing the relative accessibility of new route alignments.

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Introduction

Public transit is becoming a more acceptable alternative to the private automobile and experiencing greater use by a wider socio-economic range of people, due to higher personal transport costs, environmental concerns, and increasing congestion in urban areas. These changes influence the design and planning of transit systems. The study of the spatial results of these design changes is important to the field of transportation geography and to equity concerns. The changing accessibility of passengers to destinations that are a result of changes to the transit system is not well understood at disaggregated spatial and temporal scales.

One way to measure the change in accessibility, caused by modified transit systems, is through more detailed modeling. The main objective of this paper is to outline the construction of a high-resolution spatio-temporal, GIS-based public transit network model to capture changing accessibility. The model includes two networks: the transit network and the walking network. The integration of the two into a multimodal network allows the total travel time to include walking, waiting, and bus travel times. The second objective is to highlight the model's utility by applying it to calculate the change in relative accessibility due to new bus lines. The City of Albuquerque, New Mexico, has recently implemented two Rapid Ride bus lines, which are express, limited-stop routes, and use larger capacity buses. This application compares before and after implementation travel times, produced with the model, to Census Block Group level socio-economic attributes. The example of the utility of the model to measure the change in travel times is one measure of transportation equity, and is just one application of the model. A spatio-temporal, disaggregated transit model is useful for sustainable transportation performance measures (e.g. Zietsman & Rilett, 2008), estimating transit demand based on varying value of time (e.g. Ortúzar & Willumsen, 2001), or comparing the relative changes in accessibility for transit users between new route alignments.

While one of the current demands for expanding public transportation systems comes from the growing clamor about creating environmentally sustainable urban areas, another tenet of sustainability cannot be relegated. That is, social sustainability, specifically social justice considerations in the implementation of new public transit investments need to be given equal weight to environmental and economic sustainability concerns (Boschmann & Kwan, 2008; Martens, 2006).

The next section contains a review of the literature with time as the accessibility metric, applications of multimodal network analysis, and equity in urban transit. In the third section is a short background on the study area in which the model is applied. The fourth section details the construction and analysis of the multimodal network model. The fifth section details the results and is followed by the conclusion and discussion.

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Literature review

The model constructed for this research rests within the transportation geography fields of time as an accessibility measure and applications of multimodal network models. The example application of the model draws from the equity in transport field.

Time accessibility

Time is an essential measure of accessibility, but also entails a constraint (Kwan & Weber, 2003). Time measures are more sensitive than place-based measures since they recognize constraints imposed by demographic, social, economic, and cultural context (Miller, 2003). An example of a constraint that time imposes is the scheduling of activities between fixed time commitments, like work, to achieve other necessary activities, like doctor's appointments. This is related to the accessibility that transit can provide because the frequency and service hours can make some of these necessary, but not temporally fixed obligations unreachable by bus. The benefit of using locally specific travel times, that utilize the geometry of the street network, is a significant increase in the ability to realistically assess individual accessibility in urban areas (Kwan & Weber, 2003; Miller & Wu, 2000; O'Sullivan, Morrison, & Shearer, 2000). The addition of the provision of time within the study of accessibility comes about by the increasing realization of the diminishing explanatory power of distance, due to variations in individual travel behavior, mobility offered by the street network, and location and size of activity opportunities in traditional urban accessibility models (Weber & Kwan, 2003).

The application of using travel time as a comparative metric has been studied in-depth within the spatial mismatch hypothesis framework. This research seeks to understand and validate the hypothesized spatial differential in the locations of jobs and residences and the racial, economic, and gender disparities in the distribution in an urban area (Preston & McLafferty, 1999). The comparison of commuting time between jobs and residences among different socio-economic groups is the common approach to test the supposed disparity. Public transportation is envisioned as a possible measure to compensate for this disparity, but the actual effectiveness of this solution for reducing disparities is questionable (Deka, 2004; Sanchez, 1999). While special mismatch research is concerned with the spatial distribution of employment and residences, this also must explicitly include notions of accessibility and equity. The measurement of travel time on the public transportation network is commonly done with the construction of a multimodal network, detailed next.

Multimodal measures

To model an actual public transportation network, a multimodal representation within a GIS optimized for transportation is a common approach (Miller & Shaw, 2001). While the theoretical construction of multimodal networks and their mathematical analysis have existed for some time (e.g. Sheffi, 1985), recently new innovation and applications have been developed. One of the obstacles to the use of GIS-based multimodal network models is their overestimation of potential transit ridership (Biba, Curtin, & Manca, 2010). The renewed interest in multimodal transit network analysis is due partly to the increasing availability of parcel-level data to address this concern. This allows a more accurate distribution of population to be modeled, compared to Census Blocks. For example, Biba et al. (2010) use parcel-level data in addition to walking distance along a street network to improve the population estimate within a ¼ mile walk distance of transit stops. This improved resolution of potential transit users addresses transportation planners' concern of overestimation when using GIS for transportation planning. One extension of this research is to use this parcel-network method and include the quality, or service frequency of transit. This is one contribution that this research paper seeks to address.

Renewed interest in transit network modeling is also due in part to increased temporal precision and representation in models. For example, the recent paper of Lei and Church (2010), extend temporal elements within a transit accessibility analysis. Specifically, this is accomplished by integrating bus service times as attributes of the bus network. The advantage is to account for the travel time variability due to direction of travel, time of day, and specific start times to accomplish a more detailed representation of temporal accessibility that the transit system provides.

While these two recent articles make important contributions to the analysis of multimodal transit networks, they do not consider equity of the services analyzed. The importance of equity analyses is briefly outlined next and this research seeks to use similar approaches to measuring accessibility of a transit system, but stresses the social imperative of the transit system to equally consider those who depend on its service.

Equity in transport

The study of transportation equity ultimately seeks to "provide equal access to social and economic opportunities by providing equitable access to all places" (Sánchez et al., 2003, 10). For public transit, equitable access for users dependent on its service to the opportunities of the city is one of the fundamental goals of urban transportation planning (Liu & Zhu, 2004). There is a plurality of definitions for the concept of equity in the provision of public transportation. Examples are formal equality, in which transit provision is proportional to population, substantive equality, in which transit provision provides equality of outcomes, least social cost, in which societal costs due to transit provision are minimized regardless of equity considerations, or profit-maximizing, in which the free-market is the most appropriate provider of an efficient and just transit service distribution (Hay, 1995a). While the specific concept of equity is contested and complicated, the definition most commonly agreed upon in transit equity analyses is that of substantive equality, or distributive social justice (Hay, 1995a; Hine, 2008). This is a focus on equity of distribution, which integrates and emphasizes the importance of need, and is concerned with whether government subsides of public transit are actually reaching those in need (Deka, 2004). While it is more difficult to measure than equality of distribution, the analysis of equity can be accomplished by comparing the differing degree to which needs are met (Hay, 1995b). Furthermore, transit service provision, in this research with regard to travel time, should be proportionate to service need (Boyne & Powell, 1991). This service need is identified as the primary factor to determine equity in previous research studies, but what constitutes need is not consistently defined amongst similar studies (Deka, 2004).

The equitable distribution of the spatial and temporal accessibility that a transit system provides can be addressed through targeted economic subsidies and "services could be varied so that those suffering transport disadvantage received relatively higher levels of service" (Starrs & Perrins, 1989, 73). There is repeated recognition of the contribution of transit to potentially minimize social exclusion and increase social justice for those identified as in need (e.g. Farrington & Farrington, 2005; Hine, 2008). Additionally, there is a clear understanding that one justification for the existence of public transportation is to serve the neediest (Litman, 2007). Accessibility is a key measure that contributes to the

understanding of the spatial dimension of social justice, and increasing accessibility is one method to decrease social disparities (Farrington & Farrington, 2005).

A common measure of accessibility is based on demand, which considers only the proximity of potential users to transit stops and lines. This does not adequately capture the change in travel time that rapid bus routes enable, or the actual time window of availability of the service. The frequency of the bus service and how long users are willing to wait are significant considerations for potential transit riders (Polzin, Pendyala, & Navari, 2002). Demand also ignores the social need for the service, which it is argued, should be one of the primary considerations in public transit provision (Lucas, 2004; Martens, 2006; Talen, 2003).

One solution to the social equity shortcomings of demand based analysis is to measure travel time. For example, the decrease in travel time, due to rapid buses, can help increase the accessibility in areas of the city in which there is a social need, one of the solutions outlined by Preston and Rajé (2007) to alleviate social exclusion due to poor transportation options. Additionally, accessibility is a "community-wide public problem", not just an issue of private mobility and demand (Talen, 2003, 181). Spatial accessibility and travel time fit into the multidimensionality of accessibility as a means to measure equity. Other dimensions commonly assessed are human-behavioral, socio-demographic, and land use considerations (Farrington & Farrington, 2005).

There is a consensus about the importance of accessibility to measuring equity of distribution in transit provision. However, no consensus exists in the measurement of accessibility. The example application of the model constructed in this paper is to compare household travel time savings to socio-economic characteristics. Specifically, the comparison uses a statistical correlation to assess the equity of distribution of travel time savings, following Davies (1968). The statistical measure of territorial justice, which is social justice expanded to an area, is a high correlation between "standards of provision, and an index measuring relative needs of an area's population" (Davies, 1968: 16). Though there is no consensus as to the best measure of accessibility, the measure closest to people's experience is that of travel time (Lei & Church, 2010; Lovett, Haynes, Sünnenberg, & Gale, 2002), which is the focus of the accessibility measured in this research.

Study area

The study area is the spatial extent on which the network model rests. It includes the pertinent bus routes for the transit network portion of the model, the streets for the walking network portion of the model, and residential address points which were the origins for the model. Downtown Albuquerque was chosen as a representative destination for the application of the model. The demographic characteristics of the study area are used for the application of the model.

The area of study is located in Albuquerque, New Mexico, which had an estimated population of 504,949 and a metropolitan statistical area population of 816,811 in 2006 (BBER, 2007a, 2007b) (Fig. 1). The Westside of the city is the specific study area, defined as west of the Rio Grande. While both of the new bus lines navigate through the study area, there are stark differences in socio-economic indicators between the Northwest and Southwest areas, with much of the Southwest unincorporated into the city. The Northwest area tends to be more middle-aged, more affluent, and have a higher car ownership proportion compared to the Southwest area. For example, Fig. 2 highlights this contrast between the Northwest and Southwest areas, showing a higher proportion of households with low incomes in the Southwest region Census Block Groups. The distribution of higher proportions of no car ownership and older and younger age groups is similar to the low income distribution. The Westside, a combination of the North and South areas, had a job to housing ratio of 0.55 in 2004 (MRCOG, 2007). There are significantly more houses than jobs in the study area, which necessitates substantial commuting across the Rio Grande for employment.

The two rapid bus lines, the Red Line and the Blue Line, did not replace existing buses, but were implemented as a premium transit service. This service has the same fare as the rest of the bus system. The potential impact of rapid bus lines is a significant decrease in travel time for the riders who live within the service areas of these routes, or transfer to use them. These new routes represent a substantial improvement over the provision of traditional, local bus service in terms of travel time savings, additional capacity, and increased amenities these buses provide. However, rapid bus lines provide less spatial coverage, since their stops are farther apart, but may have a larger rider catchment area around stops, due to the higher quality of service.

As a key regional commuting destination, downtown Albuquerque, has a large concentration of jobs and due to the geography of the city there are relatively few crossing points to access the area. Downtown Albuquerque has a job density of over 28,000 per square mile, the highest in the metro area (MRCOG, 2007). The jobs in the area include office, hotel, government, and restaurant – all of which require some low-pay service jobs. Additionally, the two main campuses of higher education in the metro area are located just east of downtown, as well as the three main hospitals. Utilizing public transit from the Westside to these destinations requires going through downtown- five of the six east-west, all-day bus routes across the Rio Grande go through downtown. Finally, the downtown transit hub is local, regional, and national in function, with city and intercity buses and both regional-commuter and national rail. Due to the continued significance of downtown for employment in the region, its proximity to substantial educational and health facilities, and its primacy as a public transit node, downtown Albuquerque is chosen as a representative and pertinent point to evaluate change in public transit travel time.

Analysis methods

This paper details the development of a public transportation accessibility model and an example application. The first objective was to develop a high-resolution, multimodal model that used travel time as the accessibility measurement. The second objective was to demonstrate the applicability of the model to assess the change in travel times due to a recent addition of bus service in the study area. These results were then analyzed within a distributive equity framework. The multimodal network was developed in ArcGIS and accounts for the walking time from individual residential addresses to a bus stop, the waiting time at a bus stop, the travel time on the bus, and any necessary transfers. Travel times were calculated with an Origin/Destination analysis in the Network Analyst extension. The network was attributed with the temporal attributes of the morning peak, afternoon peak, and off-peak bus travel times and headways.

Network development

The design of the model included two network components: a walking network and a transit network. The model used the walking network to estimate walking travel times to and from the destinations and origins and the bus stops. The walking network was constructed from streets, under the assumption that they were suitable for walking (e.g. had sidewalks), but excluded freeways, which are not suitable for walking. A commonly assumed walking

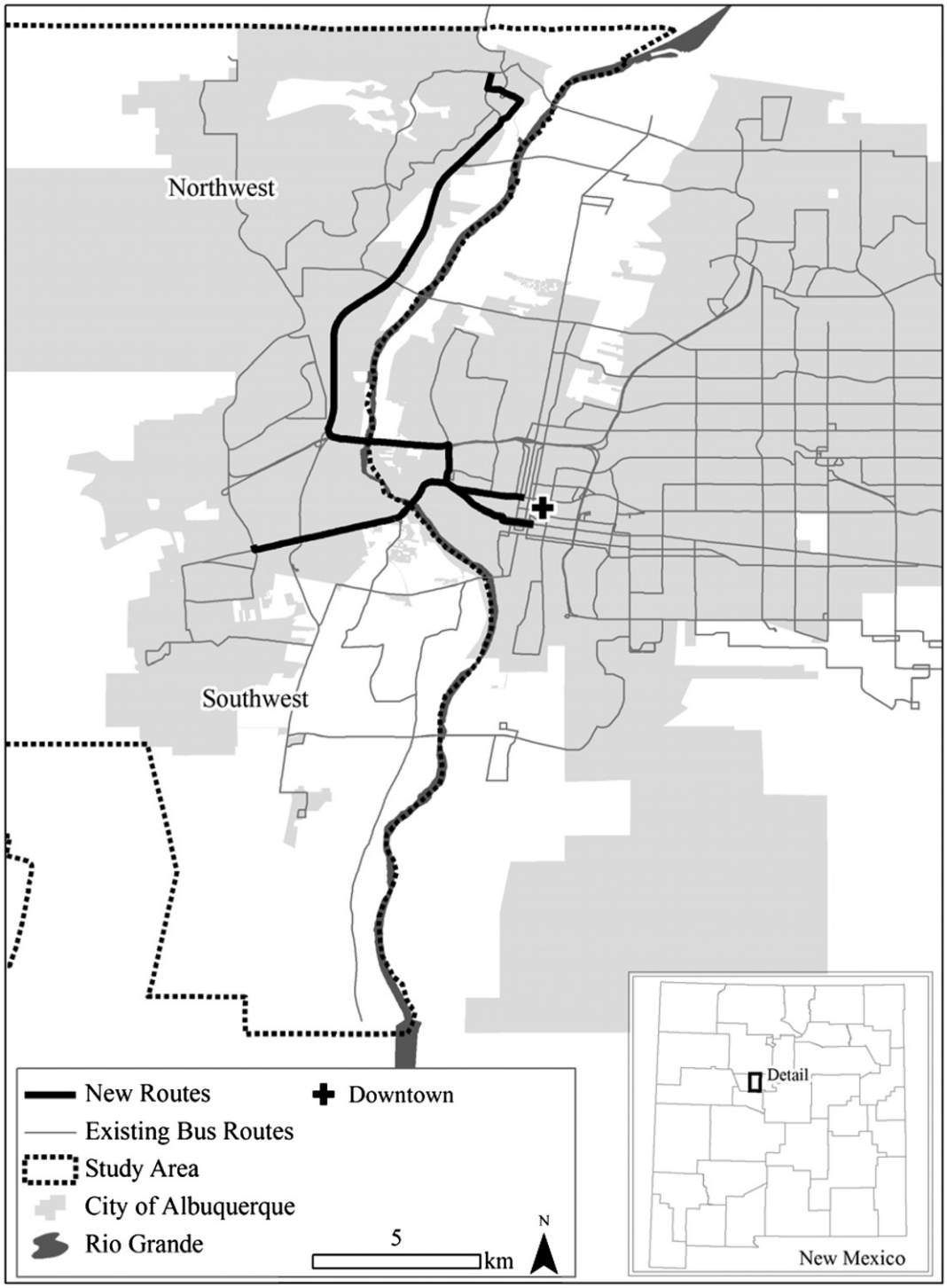

Fig. 1. Study area within Albuquerque, New Mexico with new rapid bus routes emphasized.

speed on streets, 3 km per hour, was used to calculate the walking mode travel time.

The transit network was constructed from the bus routes within the study area. In addition to the spatial components of bus routes and stops, temporal attributes were added from the city's published bus schedules. The morning peak travel time was calculated by averaging the travel time for individual buses that were scheduled to run between 7 a.m. and 9 a.m. This was calculated for each route segment between scheduled stops. The afternoon duration was calculated similarly, except it was based on the 4–6 p.m. time window. The off-peak time was calculated from the rest of the times not included in the previous two categories. To estimate the times to stops not on the published time schedules, a proportion attribute was created and multiplied by the travel time during the analysis.

The interaction between the walking network and the transit network, that is the change in mode of travel between walking and transit, was modeled by the creation of boarding and exit lines. The

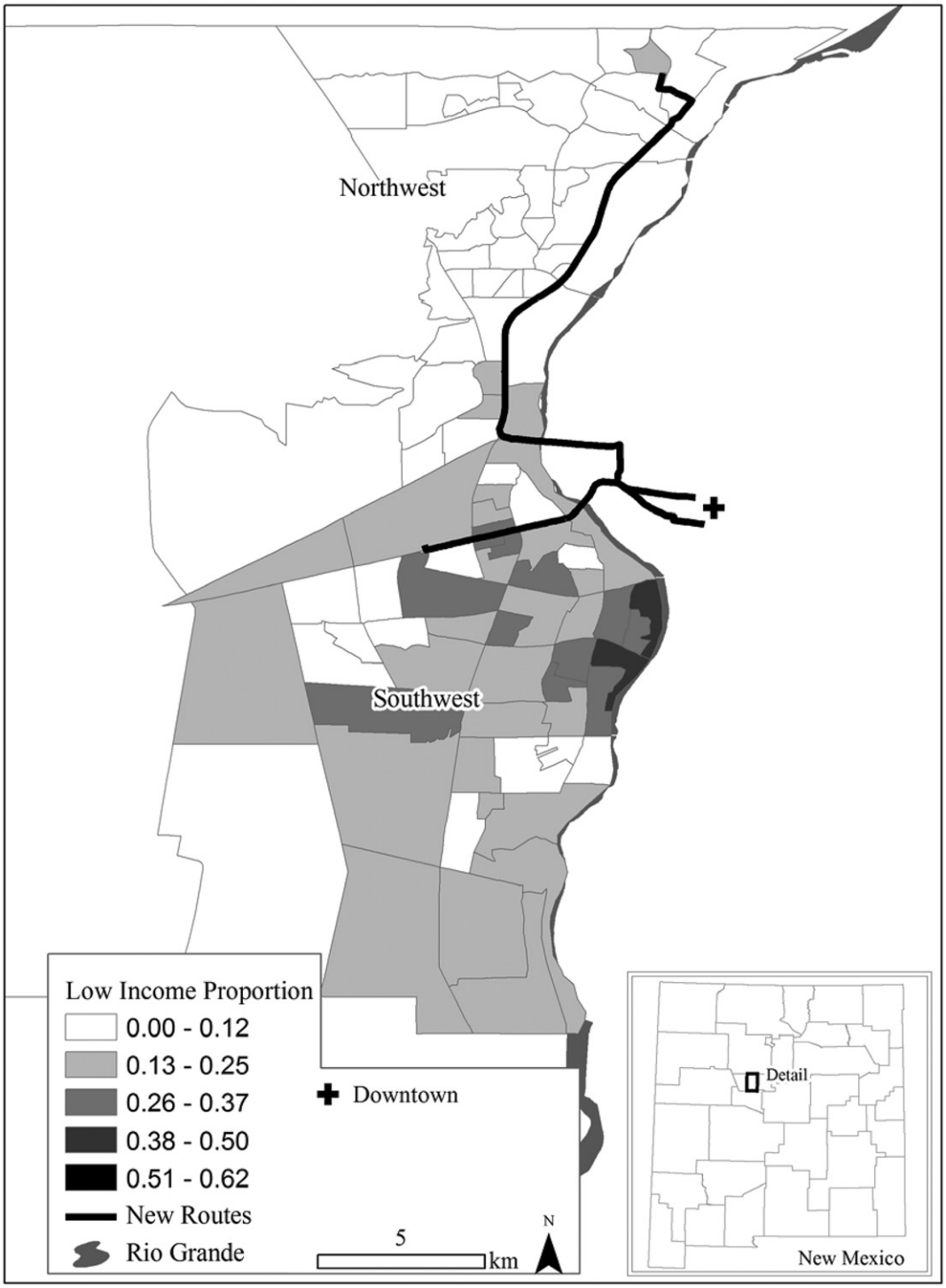

Fig. 2. Low income proportions within the westside of Albuquerque, New Mexico.

distance of these lines is ignored, as only the waiting time attribute of these lines is relevant. The bus headways were specific to stops and is the time between two successive buses servicing a stop. This attribute was derived from the published bus schedules for the same time periods as the bus travel times. The average headway time was used to approximate the passenger wait time for the bus. For example, a bus with a 30 min headway was modeled as a 15 minute passenger wait time (30 min divided by 2). To exit from the bus routes back to the street network necessitates exit lines, which were copies of the boarding lines, but traversed in the other direction. These hold no time information, and therefore no time is accumulated for exiting the bus.

The multimodal network was constructed with a detailed spatial and temporal resolution for both constituent networks. The multimodal network can capture the total travel time of walking, waiting, traveling and transfers, if necessary. The spatial detail included individual bus stops, about 4,000, to accurately capture the accessibility of the bus system and the geometry of the street

network to model realistic walking times. Attention to details in the temporal attributes resulted in the inclusion of variations in individual bus routes' travel times and headways for the morning peak, the afternoon peak, and off-peak time periods in the model. The temporal attributes also captured variations in direction of bus routes (i.e. in-bound and out-bound). The total travel time, Fig. 3, was calculated by summing the walking time on the street network from the origin, the waiting time, contained in the boarding line, the travel time on the route, and finally, exiting the route and continuing on the walking network to the destination. This meets the first objective of this research, to create a high-resolution, multimodal model that used travel time as the measurement.

Network analysis

The network was analyzed for the morning peak time period from the residential address points in the study area to downtown, which is taken to be the Alvarado Transportation Center. Within Network Analyst, the morning peak time period attribute was chosen as the impedance. This models the morning commute based on walking to the nearest bus stop, waiting for the bus and riding it to downtown. If the trip required a transfer, this was accounted for, as well, and it required additional waiting time for the transfer (Fig. 4). The total travel time between the address points and downtown was calculated for the base bus route network and one with the addition of rapid buses. The difference between these two travel time scenarios resulted in the travel time savings for each address point.

The second object of this research is the social justice application of the model results. This required the output of the model, the travel time savings at address points, to be compared with socio-economic characteristics at the Census Block Group. The address points were aggregated to the Block Groups and the weighted average travel time was calculated. The weighted average time was necessary due to the address points representing house or apartment parcel centroids and not taking into consideration the number of residents living at each point. The weight for each point was obtained by a land use layer which contained housing type and number of units for apartments. The residential units were the basis of the weights. The selected socio-economic variables—low income, car-less, older than 65, and younger than 19—reflect commonly used indicators for areas of transit need. The significance of the chosen groups can be seen in targeted economic subsidies, which is an attempt to redistribute income, or at least

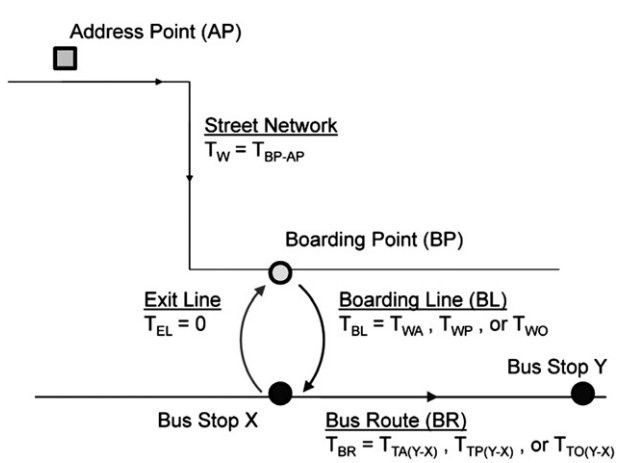

Fig. 3. Diagram of the accumulation of travel time, in which the total time is calculated by taking the sum of T_W, T_{BL}, and T_{BR}, the latter two of which depend on the time period analyzed.

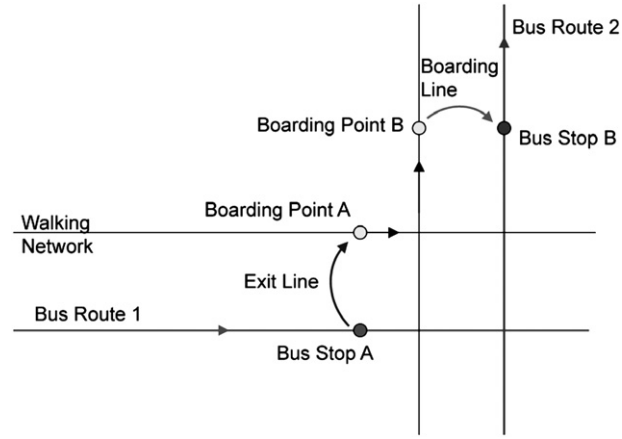

Fig. 4. Schematic of transfers between bus routes, which requires exiting the current route, Bus Route 1, through an exit line, traversing the walking network, and boarding the second route, Bus Route 2.

reduce inequities (Starrs & Perrins, 1989). For example, handicapped, Medicare recipients, elderly, and youth all pay a reduced fare on buses in the city of Albuquerque and roughly follow the chosen variables. These indicators were taken from the 2000 Census and calculated as proportions of the total population for each of the Block Groups, the finest level of spatial detail available. The relevance of these indicators to the study area is revealed by Fig. 2, as previously discussed.

To simplify the visual comparison between the travel time savings and areas of transit need, a transit users' index was created. This is an equally weighted average of the selected variables' proportion. This index attributes Block Groups with a relative proportion of transit need and allows for a summary of the socio-economic indicators into one variable to ease comparison, following Boone, Buckley, Grove, and Sister (2009) and Talen (2003). This index is standardized between 0 and 1. The closer this number is to 1, the higher social need for transit service, due to a higher proportion of lower income residents, a higher proportion of no car ownership households, and a higher non-driving age population proportion. The closer the index is to 0, the lower the social need for transit service, due to higher incomes, higher car ownership, and lower non-driving age population proportions. This index provides a relative need for a given Block Group, as the Block Groups are not decisively categorized as in social need of transit or not.

Results

The first result was the construction of the multimodal public transportation model, which allowed for the visualization of travel time savings at the individual address point level. An example of the significance of this result, Fig. 5, shows of the time savings at the address point level around the Montano Plaza rapid bus stop. This result is from the address points to downtown during the morning peak scenario and highlights the usefulness of including a detailed walking network in the analysis. The time saving from the addition of the rapid bus to the area, specifically the influence of the stop, is not constant for address points in an equal radius from the stop. The time savings vary, as demonstrated by the 500 m buffer, depending on the walking network grid and the accessibility it provides. Not all points within the buffer see the same time savings, and this is particularly true for the limited access of the neighborhoods around Coors Blvd. The addresses closer to the access road see a greater savings, even though they

Fig. 5. Detail of address point travel time savings attributes around a rapid ride stop, with 500 m buffer.

may have a farther straight-line distance than other addresses. This example underscores the usefulness of the street network as the basis for walking accessibility to bus stops. Also, in Fig. 5, two address points near Montano Rd and Coors Blvd are labeled and demonstrate the necessity of weighting the address points when looking at the average time for the Block Groups. Both of these points were given a weight of 50, since they represent at least 50 units, and need to reflect this when combined with points that represent single-family homes, when aggregating the points to the Block Group level.

A complete address point time savings map, in Fig. 6, shows the concentration of the time saving in the northern portion of

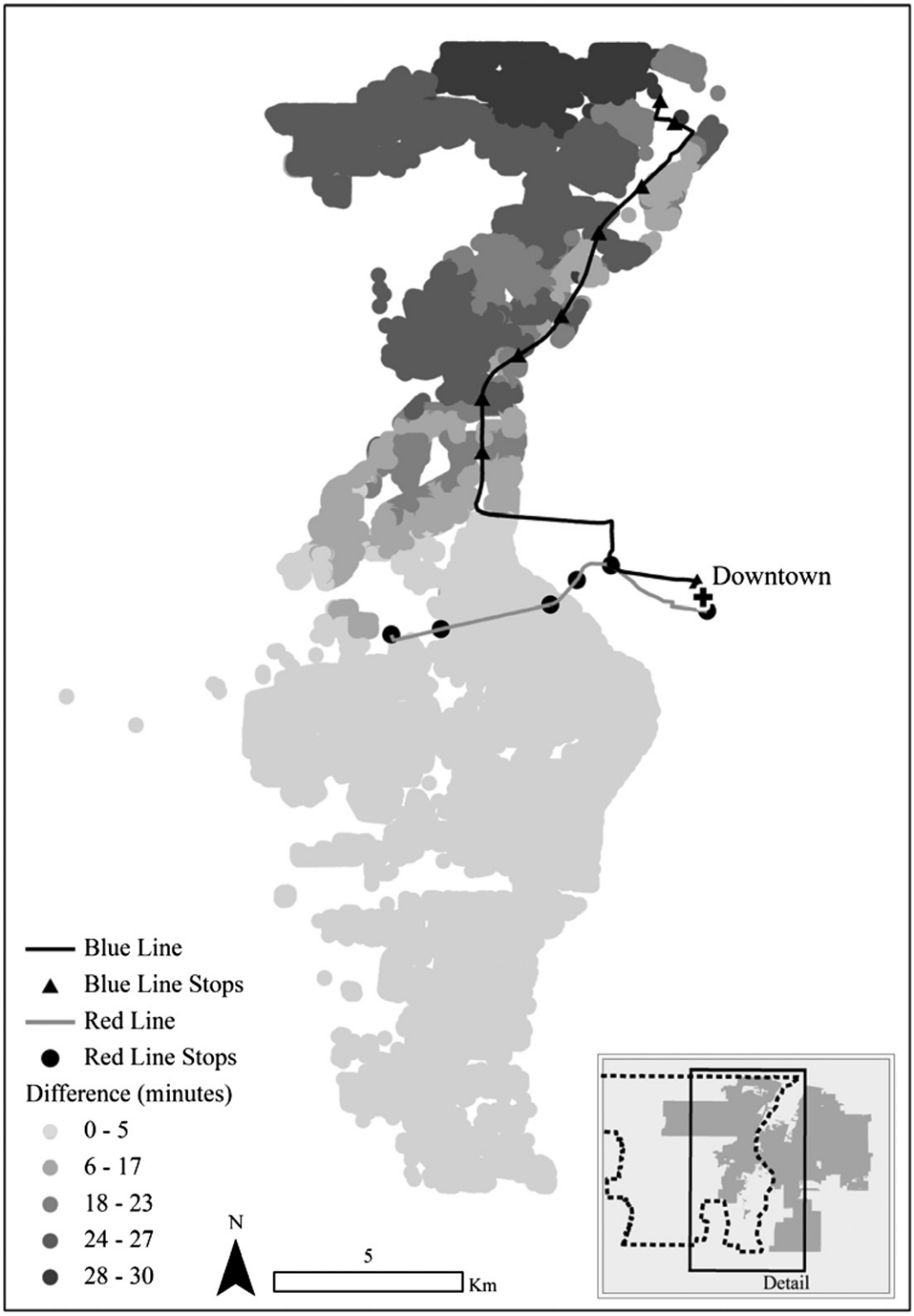

Fig. 6. Travel time saving of residential address points for the A.M. commute to Downtown.

the study area, whereas the southern portion realizes no time savings. These travel time savings were then standardized to a percent of total travel time and aggregated to the Census Block Group level. A visual comparison of the percentage of average weighted travel time savings by block group and the transit users' index by block group shows a stark contrast between the location of significant time savings and the location of areas of transit need (Fig. 7). The clustering of areas of transit need in the southern half of the study area, near the Red Line and farther south, is apparent. These areas experience the least benefit of the new bus route alignments, however, with less than 5 percent in travel time savings. Very few individual residential points

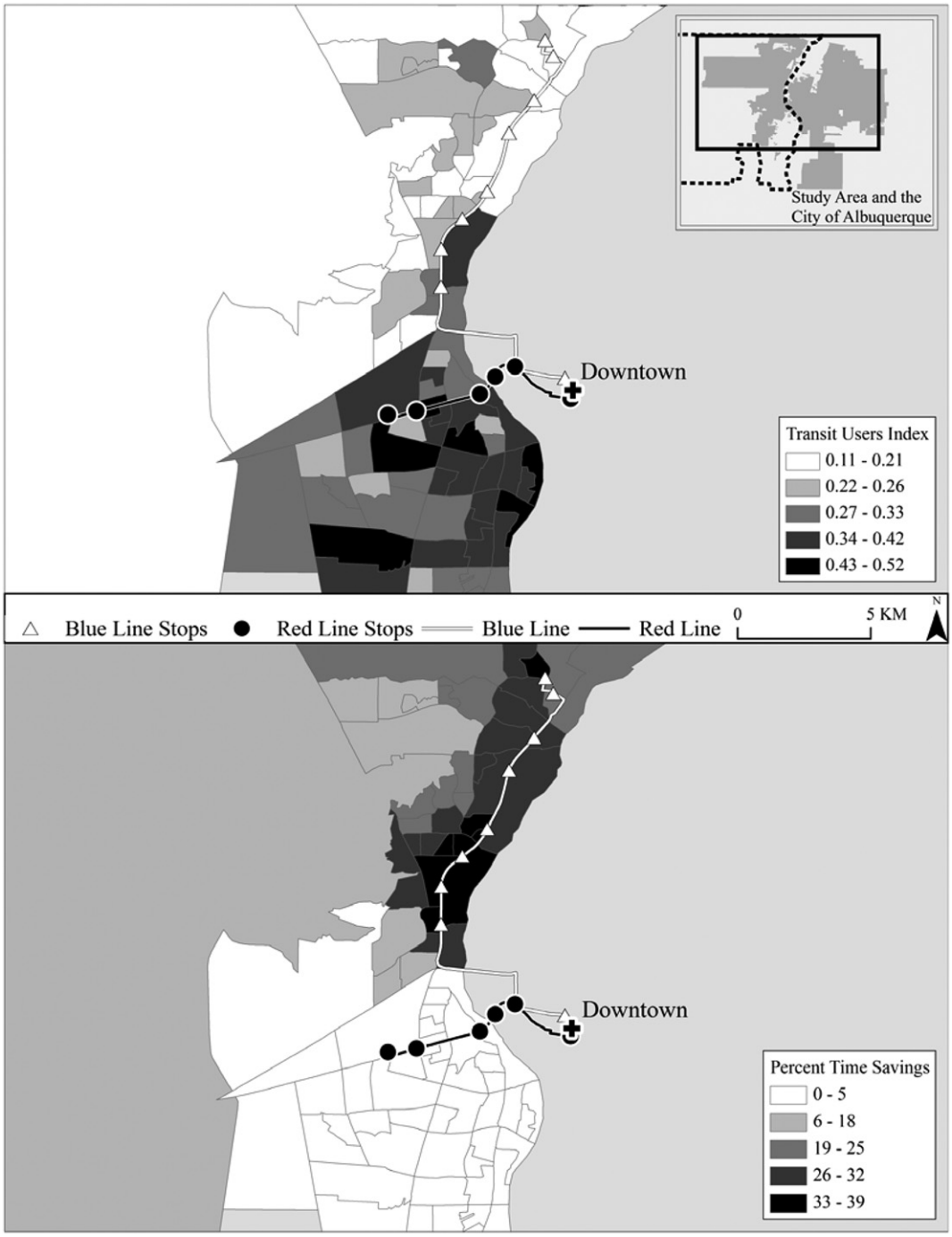

Fig. 7. Transit population proportion relative to the rapid rides, by census block group (TOP). Percent travel time savings relative to the rapid rides, by census block group (BOTTOM).

experience significant time saving in the block groups near the Red Line stops however, despite their proximity. This is due to the street, Central Avenue, having a relatively frequent local bus route before and after the new route implementation and therefore little change in temporal accessibility is realized. This is also attributable to the lack of a dedicated transitway for the Rapid Ride, so it is victim to the same congestion effects on travel time as the local bus in this corridor. This analysis also takes into consideration riders on buses from the south transferring to the Red Line into downtown, which results in little benefit for these users as well.

A statistical comparison of the block groups confirms what is visually apparent. There is a negative correlation between the selected transit users' indicator variables and the percent travel time savings due to the Rapid Rides (Table 1). These are Spearman Rank correlations, as neither the percent time savings nor the socio-economic variables were normally distributed. The interpretation of the negative correlation is that the greater the percent travel time savings, the lower the transit users' index. The strongest negative correlation, among the variables and travel time savings, is with the transit users' index, which confirms the visual relationship evident above. The low income proportion and combined age

Table 1
Percent average time difference (PTAD) correlations with transit users' variables.

	Transit index	Low income proportion	Combined age proportion	No car proportion
PTAD	−0.690	−0.661	−0.650	−0.335

proportion also have strong negative correlations with travel time savings.

Discussion and conclusions

The creation of a high-resolution spatio-temporal, GIS-based public transit network model to assess the changes brought about by new routes can highlight the travel time savings for individual address points. This is accomplished with consideration of bus frequencies and travel times for specific travel periods and the inclusion of walking time on the street network. Not only can this method be used to analyze various scenarios in an existing public transportation network, but it can be utilized to assess the detailed effects about future route alignments and stop placement to better inform transportation planning decisions. Additional applications are computing sustainable transportation measures and estimating transit demand based on varying value of time. Travel time to and from individual weighted residential addresses to various destinations can be analyzed and mapped. The comparison of calculated times allows the selection of route alignment for the largest travel time benefit to the greatest number of people. This is not a vague notion of population at the Census Block level, but at the residential address parcel-level.

The application of this model was to determine whether the distribution of travel time savings due to new bus routes was equitable. This analysis prioritized transit service need, as outlined as a significant area of study. The current methods and level of simplification of public transportation accessibility studies are not detailed enough to capture travel time at the household-level and at varying times of day. With this model, social justice issues can be analyzed at a finer level of detail. Specifically, this study presents the results of the spatial distribution of the temporal benefits that the Rapid Ride bus service provides. This time benefit distribution does not follow spatially defined socio-economic patterns of need. These areas of need had poor temporal transit accessibility before the initiation of the Rapid Rides, but did not see an improvement afterwards. The households that benefit with the greatest percentage time savings from the new route alignments, in the northern portion of the study area, are not where the greatest proportion of transit users are located, in the southern portion of the study area. There is not a high correlation between "standards of provision, and an index measuring relative needs of an area's population" (Davies, 1968: 16), but the opposite – a high negative correlation. Therefore, territorial justice, and distributive social justice, was not accomplished in the implementation of the Rapid Ride routes in Albuquerque, NM. This is contrary to US Federal policy on environmental justice to "[e]nsure that new investments and changes in transit facilities, services, maintenance and vehicle replacement deliver equitable levels of service and benefits to minority and low income populations" (Federal Transit Administration, 2000, 9).

The results of the negligible impact of the Red Line on travel time savings does not indicate that the southern area was equitable, well served with frequent buses, before the new routes. The Red Line could have had a larger impact had its alignment been routed farther into the southern area of the Westside. The southern area is serviced by buses with frequencies of over 30 min, so the potential benefits of this more equitable alignment would have been dramatic. In striving toward a more equitable public transportation system, the socio-economic need of residents in the city should be considered chiefly when implementing new routes, not just the consideration of potential demand or new riders (Kenyon, Lyons, & Rafferty, 2002; Martens, 2006).

A strictly spatial analysis of the bus system, for example a commonly used metric of proportion of transit need areas within a quarter mile buffer of bus stops, would not necessarily uncover the inequities revealed here (MRCOG, 2004). Looking at the study area map, Fig. 1, it is clear that the spatial distribution of bus routes in the study area is spread fairly equally. To conclude from this observation that there are no inequities in public transit provision would grossly over-simplify one of the most significant considerations in travel: that of travel time, including walking, waiting, and transferring (Beimborn, Greenwald, & Jin, 2003). There was a possibility that the Southwest area could have benefited by transferring to the new service to save time, but this was not the result. This analysis prioritized the travel time accessibility measure, which also implicitly included physical accessibility, though it does have limitations.

This model does not take into consideration actual conditions of the street network, such as if sidewalks are present, or more qualitative effects, such as safety, riders actual use of the bus system, versus optimized. Other temporal considerations omitted were particular users' time budgets for travel and the subsequent restriction that places on travel distance, the bus system's operating hours, and the significance of the effect of congestion on travel time savings. Specifically, this model used average travel and waiting times, as opposed to actual travel times. These average times were based on published schedules, so they represent the finest level of temporal detail. The approximation of wait times by averaging headways is not unproblematic. As headways move outside the range of 6–11 min, passengers are expected to know the schedule and wait time remains near constant (Fan & Machemehl, 2009; Vuchic, 2005). The gravity of downtown as the representative commuting destination is debatable. Downtown is a center of a significant number of jobs, but Albuquerque is a low density city and employment is but one consideration to reduce social exclusion, others being education and training, health care, and entertainment opportunities (Lucas, 2004). The major education and health care opportunities are located a short distance east, but require passage through downtown if accessed by bus from the study area.

This is not to imply that these routes do not have a positive impact upon the city. The results indicate that residents in the northern part of the study area did see a significant increase in travel time savings, increasing the likelihood of public transit being chosen over commuting by automobile. This would lead to a decrease in congestion and pollution in the city. But, to focus on the reduction of environmental pollution, and on environmental sustainability more broadly, omits another tenet of sustainability, social sustainability. The emphasis on environmental sustainability in the transport sector overshadows social sustainability issues, specifically social equity, though they need to be given equal consideration (Boschmann & Kwan, 2008; Martens, 2006). The chosen route alignments of the Rapid Ride appear to be servicing areas other than those with the highest transit need.

The construction of a detailed household-level temporal accessibility model to assess changes caused by these new routes highlighted the travel time savings with consideration of bus frequencies and travel time for specific travel periods, walking time on the street network, and the use of address points. The travel time savings was visually compared and statistically tested for significance, with strong negative Spearman Rank correlations that were

highly significant. The finding of this research is the unequal allocation of travel time savings to transit user concentrations based on socio-economic need. Though, the implementation of the Rapid Ride routes was not necessarily to benefit traditional transit users, as the ridership statistics indicate, but choice commuters and in this regard it was successful.

References

Beimborn, E. A., Greenwald, M. J., & Jin, X. (2003). Accessibility, connectivity, and captivity: impacts on transit choice. *Transportation Research Record, 1835*, 1–9, Paper number 03–2336.

Biba, S., Curtin, K. M., & Manca, G. (2010). A new method for determining the population with walking access to transit. *International Journal of Geographical Information Science, 24*(3), 347–364.

Boone, C. G., Buckley, G. L., Grove, J. M., & Sister, C. (2009). Parks and people: an environmental justice inquiry in Baltimore, Maryland. *Annals of the Association of American Geographers, 99*(4), 767–787.

Boschmann, E. E., & Kwan, M.-P. (2008). Toward socially sustainable urban transportation: progress and potentials. *International Journal of Sustainable Transportation, 2*(3), 138–157.

Boyne, G., & Powell, M. (1991). Territorial justice: a review of theory and evidence. *Political Geography, 10*(3), 263–281.

Bureau of Business and Economic Research (BBER), University of New Mexico. (2007a). *New Mexico metropolitan statistical areas, 2000 to 2006*. Albuquerque, NM: BBER.

Bureau of Business and Economic Research (BBER), University of New Mexico. (2007b). *Population estimates for New Mexico incorporated places*. Sorted Alphabetically. June. Albuquerque, NM: BBER.

Davies, B. P. (1968). *Social needs and resources in local services*. London: Michael Joseph.

Deka, D. (2004). Social and environmental justice issues in urban transportation. In S. Hanson, & G. Giuliano (Eds.), *The geography of urban transportation*. New York: Guilford Press.

Fan, W., & Machemehl, R. B. (2009). Do transit users just wait for buses or wait with strategies? *Transportation Research Record No, 2111*, 169–176.

Farrington, J., & Farrington, C. (2005). Rural accessibility, social inclusion and social justice: towards conceptualization. *Journal of Transport Geography, 13*(1), 1–12.

Federal Transit Administration. (2000). *An overview of transportation and environmental justice*. Publication No. FHWA-EP-00-013. http://www.fhwa.dot.gov/environment/ej2000.pdf Last accessed 15 January 2011.

Hay, A. (1995a). Equity and welfare in the geography of public transport provision. *Journal of Transport Geography, 1*(2), 95–101.

Hay, A. (1995b). Concepts of equity, fairness and justice in geographical studies. *Transactions of the Institute of British Geographers New Series, 20*(4), 500–508.

Hine, J. (2008). Transport and social justice. In R. Knowles, J. Shaw, & I. Docherty (Eds.), *Transport geographies: Mobilities, flows, and spaces*. Malden, MA: Blackwell Publishing.

Kenyon, S., Lyons, G., & Rafferty, J. (2002). Transport and social exclusion: investigating the possibility of promoting inclusion through virtual mobility. *Journal of Transport Geography, 10*, 207–219.

Kwan, M.-P., & Weber, J. (2003). Individual accessibility revisited: implications for geographical analysis in the twenty-first century. *Geographical Analysis, 35*(4), 341–352.

Lei, T. L., & Church, R. L. (2010). Mapping transit-based access: integrating GIS, routes and schedules. *International Journal of Geographic Information Science, 24*(2), 283–304.

Liu, S., & Zhu, X. (2004). An integrated GIS approach to accessibility analysis. *Transactions in GIS, 8*(1), 45–62.

Litman, T. (2007). *Evaluating transportation equity*. Victoria, BC, Canada: Victoria Policy Institute. www.vtpi.org/equity.pdf Last accessed 1 November 2008.

Lovett, A., Haynes, R., Sünnenberg, G., & Gale, S. (2002). Car travel time and accessibility by bus to general practitioner services: a study using patient registers and GIS. *Social Science & Medicine, 55*, 97–111.

Lucas, K. (Ed.). (2004). *Running on empty: Transport, social exclusion and environmental justice*. Bristol, UK: The Policy Press.

Martens, K. (2006). Basing transport planning on principles of social justice. *Berkley Planning Journal, 40*, 1–17.

Mid-Region Council of Governments (MRCOG). (2004). *Environmental justice Atlas and data book for the Albuquerque metropolitan planning area*. Albuquerque, NM: Mid-Region Council of Governments.

Mid-Region Council of Governments (MRCOG). (2007). *2030 Metropolitan transportation plan*. Albuquerque, NM: Mid-Region Council of Governments.

Miller, H. J. (2003). What about people in geographic information science. *Computers, Environment, and Urban Systems, 27*, 447–453.

Miller, H. J., & Shaw, S.-L. (2001). *Geographic information systems for transportation: Principles and applications*. New York: Oxford University Press.

Miller, H. J., & Wu, Y.-H. (2000). GIS software for measuring space-time accessibility in transportation planning and analysis. *Geoinformatica, 4*(2), 141–159.

O'Sullivan, D., Morrison, A., & Shearer, J. (2000). Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. *International Journal of Geographical Information Science, 14*(1), 85–104.

Ortúzar, Dios, Juan de, & Willumsen, L. G. (2001). *Modelling transport*. Chichester, West Sussex, UK: John Wiley & Sons.

Polzin, S. E., Pendyala, R. M., & Navari, S. (2002). Development of time-of-day-based transit accessibility analysis tool. *Transportation Research Record, 1799*, 35–41, Paper number 02–2226.

Preston, V., & McLafferty, S. (1999). Spatial mismatch research in the 1990s: progress and potential. *Papers in Regional Science, 78*(4), 387–402.

Preston, J., & Rajé, F. (2007). Accessibility, mobility, and transport-related social exclusion. *Journal of Transport Geography, 15*(3), 151–160.

Sanchez, T. W. (1999). The connection between public transit and employment: the cases of Portland and Atlanta. *Journal of the American Planning Association, 65*(3), 284–296.

Sanchez, T. W., Stolz, R., & Ma, J. S. (2003). *Moving to equity: Addressing inequitable effects of transportation policies on minorities*. Cambridge, MA: The Civil Rights Project at Harvard University.

Starrs, M., & Perrins, C. (1989). The markets for public transport: the poor and the transport disadvantaged. *Transport Reviews, 9*(1), 59–74.

Sheffi, Y. (1985). *Urban transportation networks: Equilibrium analysis with mathematical programming methods*. Englewood Cliffs, NJ: Prenticle-Hall.

Talen, E. (2003). Neighborhoods as service providers. *Environment and Planning B, 30*(2), 181–200.

Vuchic, V. R. (2005). *Urban transit: Operations, planning, and economics*. Hoboken, NJ: J: Wiley & Sons.

Weber, J., & Kwan, M.-P. (2003). Evaluating the effects of geographic contexts on individual accessibility: a multilevel approach. *Urban Geography, 24*(8), 647–671.

Zietsman, J., & Rilett, L. R. (2008). Using sustainable transportation performance measures in corridor decision making. In *Towards a definition of measurable environmentally sustainable transport, proceedings of seminar: COST 356 Oslo, Norway, February 20, 2008*. Oslo: Institute of Transport Economics.