Direct Ridership Models of Bus Rapid Transit and Metro Systems in Mexico City, Mexico

Nicolae Duduta

Direct ridership models (DRM) have been introduced in the United States as an alternative to four-step travel demand modeling. DRMs can be used to obtain quick, order-of-magnitude estimates of transit patronage at a fraction of the cost of a full travel demand model and are more adept at capturing the effects of smart growth on transit ridership. The relatively low cost, flexible data requirements, and rapidity make these models particularly suited to developing world cities. Yet these cities still rely almost exclusively on full travel demand models to advise investments in new transit infrastructure. In doing so, cities often use old data and out-of-date household surveys and do not capture important recent changes in travel patterns. Mexico City, Mexico, is taken as a case study to illustrate the benefits of using DRM models in a developing world context. Ridership models are developed for the city's bus rapid transit and Metro networks to study how land use and service and station attributes affect ridership for each mode and also how connections between bus rapid transit and Metro affect each other's ridership. The two systems are complementary, each getting ridership benefits from connecting to the other. Implications of findings for transport policy in Mexico City are discussed, as well as some shortcomings of DRM models, particularly their difficulty in accounting for informal transit.

Direct ridership models (DRM), also known as off-line ridership models, have emerged in the United States as a rapid, low-cost alternative to full travel demand models. DRM models use regression analysis to directly predict demand at specific nodes in a transport network, such as transit stations, as a function of neighborhood, station, and service attributes (*1*). What sets these models apart from other travel demand modeling techniques is that they do not use the origin–destination attributes of trips, and therefore, some of the variables that would commonly show up in a mode choice model, such as the comparative cost and travel times of different modes, are absent (*2*).

Cervero et al. suggest that the independent variables commonly used in DRM models can be classified as three main sets (*2*):

- Service attributes. Frequency of service and operating speeds along the trunk line under study, as well as the number and frequency of feeder routes;
- Location and neighborhood attributes. Population and employment densities in the station area, size of the catchment area, type of station (e.g., terminal), and so on; and
- Station attributes. Presence of user information systems, parking availability, and so on.

The models are quite flexible and can adapt easily to the types of data available locally. For example, in the case of a ridership model for the Bay Area Rapid Transit (BART) system in the San Francisco Bay area in California, the catchment size of a station was defined as the contiguous area that historically captured 90% of all access trips to and egress trips from the station (*3*). This was possible in the case of BART because the system was already in place and there were surveys available to clearly establish the size of the catchment area. In the case of the Charlotte, North Carolina, Transitway, for which a DRM model was developed to help plan for the system, the catchment size was alternately defined as the distance to the nearest adjacent station (*1*). Similarly, station area density has been accounted for in different ways in the literature: as residents per gross acre, jobs per gross acre, a combination of both, or an interactive variable combining the effect of the central business district's (CBD) size and its density (i.e., employees per acre multiplied by total employees) (*1*). Because of this flexibility, DRM models can use available data and usually do not require extensive additional data collection, a major plus from the perspective of a developing world city.

Their emphasis on station area attributes such as density, mixed use development, and parking availability makes DRM models more adept than four-step models at capturing the ridership benefits of smart growth (*1*). This is also because DRM models are developed at a very fine grain, looking at the attributes of each station area, while four-step models rely on much larger traffic analysis zones and have more difficulty capturing local land use impacts on travel demand (*1*). As a result, DRM models have gained traction in the United States for estimating the ridership benefits of transit-oriented development (TOD) (4).

However, since each observation in a DRM model is a transit station, sample sizes are usually small, ranging in the literature from a high of 261 in a nationwide TCRP model (*3*) to a low of 27 for a model of St. Louis, Missouri, MetroLink stations (*1*). The low sample sizes often limit the number of variables that can be introduced in the models and their specification (*2*). As a result, DRM models are used primarily as sketch planning tools, providing quick order-of-magnitude estimates useful for comparing different corridor alignments or land use scenarios. In particular, log-log models (i.e., those that predict the natural log of boardings as a function of the natural log of each independent variable) are useful policy tools.

EMBARQ Center for Sustainable Transport, 10 G Street, Suite 800, Washington, DC 20002. N. Duduta, nduduta@wri.org.

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They can express the relationship between, for example, station area density and boardings as a percent change in one affecting percent change in the other, and that is very easily translatable into policy.

To date, direct models have been estimated in the United States for different types of transit systems, ranging from bus rapid transit (BRT) (*2*) to light rail (*1, 3*), Metro (*1, 3*), and commuter rail (*3*). As far as is known, this technique has not been applied and evaluated in a developing world context.

Only a brief overview of the main features of DRM models is provided here, focusing on those characteristics relevant for adapting the models to the context of a developing country. Cervero et al. provide a more in-depth discussion of DRM models, and a comparison with traditional four-step travel demand models (*1, 2*).

APPLICABILITY OF DRM MODELS IN DEVELOPING WORLD CITIES

Common Techniques and Challenges in Estimating Travel Demand

In many developing world cities—especially second- and third-tier cities, which are now experiencing most of the population growth—local transport professionals often lack in-depth expertise in travel demand modeling. In fact, one of the most iconic mass transport systems of the developing world, the Curitiba BRT in Brazil, was built without any formal traffic modeling (*5*). While modeling capacity is limited, the challenges for developing accurate estimates are greater than in the developed world, including rapid urbanization and motorization, as well as poor data quality and availability. As a result, it is not uncommon for ridership projections to greatly overestimate or underestimate demand. The actual passenger demand on the Janmarg BRT in Ahmedabad, India, exceeded the forecasts, and the initial bus fleet proved to be insufficient to meet the demand (*6*). Conversely, initial passenger demand on the Metrobús-Q BRT in Quito, Ecuador, fell below expectations, running the risk of causing major financial problems for the private operators (*6*).

Planners have recognized these issues and have created tools for developing rapid demand assessments for new rapid transit routes—particularly BRT—using only bus traffic counts, bus speed measurements, and quick occupancy surveys at key locations (*5*). These types of tools are appropriate for new rapid transit corridors that replace existing transit routes, usually consisting of conventional buses, minibuses, and various forms of informal transit. They are based on the assumption that the new system will replace the older transit service on the route, and most passengers on the new systems will be former riders of the previous ones. This assumption is supported by data from BRT user surveys in Mexico City, Mexico, indicating that around 80% of them had switched to BRT from other transit services (*7*).

These rapid assessment tools can be used to generate order-of-magnitude ridership estimates, which can then inform the type of infrastructure and technology required to meet that demand. The *Bus Rapid Transit Planning Guide* offers a table that suggests the type of BRT configuration most suited for broad ranges of demand (*5*). For example, from 2,000 to 8,000 passengers per hour per direction (pphpd), the guide recommends a simple median busway; from 8,000 to 15,000 pphpd, it recommends a segregated median busway with off-board fare collection, and so on (*5*).

Although these tools can be very effective at obtaining rough estimates of ridership, they rely only on existing demand in the corridor, and they do not account for the effects of station area development on ridership. Also, they fail to capture the impact of other factors, such as increased connectivity, on ridership. For example, the implementation of Line 2 of the Metrobús BRT in Mexico City increased ridership on Line 1, and improvement of the transfer between the two lines increased it further (*8*). The rapid assessment tools can inform on the best corridor configuration, but they are not useful for informing integrated transport and land use policy.

At the other end of the spectrum, there are the full travel demand models that transit agencies and consulting firms in the developing world use. One example is the ridership forecast for the future Line 12 of the Mexico City Metro. It uses data from a household travel survey to generate detailed ridership projections by station and by hour of the day for the new line (*9*). While this is a very accurate travel demand modeling technique, it relies on an origin and destination survey dating from 2007. The city's transport system has changed considerably since 2007, with the notable introduction of Metrobús BRT Lines 2, 3, and 4 serving the downtown area, and that has increased system-wide Metrobús ridership from 200,000 to more than 700,000 daily passengers. These BRT routes have attracted riders mostly from other transit services—especially microbuses—but also from private cars and taxis (*7*). In addition, the implementation of BRT has resulted in considerable changes to the street infrastructure along the corridors, including rerouting or eliminating microbus routes, lane closures, and turning prohibitions, all of which have an impact on travel patterns and are not captured in the older survey.

Household surveys are costly and time consuming to develop, and it is rarely feasible to update them more frequently than every 5 or 10 years (*10*). In the United States, a 5-year-old household survey should generally provide an accurate picture of the current situation. But this is rarely the case in the developing world. This situation is illustrated by example from Mexico City, one of the slower-growing metropolises of the developing world, and where a survey from 2007 is already out of date.

In addition, full travel demand models usually estimate ridership for when an entire corridor or transit system is fully built out. In the case of the TransOeste BRT in Rio de Janeiro, Brazil, which opened in June 2012, ridership forecasts apply to 2016, when the entire 150-km (93-mi) Rio BRT network will be fully built out, including connections to the Metro. In the meantime, the operating agency is left to deal with a partly built network and a fraction of the projected ridership. The challenge now faced by TransOeste is to find ways to increase ridership to a level that would at least cover operating costs, while awaiting completion of the other lines (*11*). The Suburbano commuter rail in Mexico City is currently facing a similar problem. The system is operating at a fraction of its project ridership, with negative financial implications for the government agency overseeing its operation. One of the challenges there is that ridership projections apply to 2030, when a number of additional BRT and feeder lines are expected to connect to Suburbano (*12*). Similarly to TransOeste, Suburbano needs to devise ways to increase ridership in the meantime, to cover operating costs.

Potential Role for Direct Ridership Modeling

Travel demand estimates in developing world cities are usually developed using one of the two options as mentioned: rapid demand assessments or full travel demand models. Given the challenges faced by both, it seems that direct ridership modeling could fill a niche between the two ends of the spectrum, as a more robust technique than rapid assessments and a more flexible and less costly tool than full travel demand models.

This concept was tested by developing DRM models for Mexico City's BRT and Metro networks. It was found that the models were as useful as rapid assessment tools in providing order-of-magnitude ridership estimates. In addition to their predictive value, they offered several key policy insights, which rapid demand assessments fail to do. First, the BRT and Metro networks were shown to be complementary instead of competitors, each benefiting in ridership from connections to the other. Terminal stations were shown to provide huge ridership benefits to both systems, indicating a significant underprovision of quality transit at the periphery of the metropolis. Better network connectivity, measured as the number of lines connecting at a station, and direct access to the downtown, were both correlated with higher ridership. Also, several drawbacks were identified to the use of DRM models in the developing world—particularly their difficulty in accounting for informal transit, and the fact that in some cases, their data requirements are still too strict for what is commonly available in the developing world.

MODELING APPROACH

An important choice about the modeling approach was whether to develop a single model for both the BRT and Metro systems, or to develop separate models. There is a precedent in the literature for including two types of transit systems within the same DRM model and using a technology dummy variable to distinguish them (*1*). However, that case involved two rail-based systems, BART and Caltrain (a commuter rail line) in the San Francisco Bay Area. The considerable differences in technology and capacity between BRT and Metro suggested that separate models were more appropriate. Doing this would also enable better studying of their interactions, by looking at how they are each affected by the other system's presence at a station.

Another important choice was whether to have a single Metro model for the entire metropolitan area or to split it in two: one within the CBD and one outside it. There is evidence in the literature that stations in the CBD have quite different attributes than those outside it (*1, 3*). In particular, stations in the CBD have considerably more ridership, since the CBD is a major destination in any transit system, and it can be expected to have a higher proportion of walk-on riders. Stations toward the periphery, in contrast, usually have more transfer to other routes and fewer walk-on riders. In the literature, this was dealt with by either creating a dummy variable for the CBD (*1*) or by creating a separate model for the area outside the CBD (*3*). In this case, it was decided to create two separate models: one for the CBD and another one for the area around it.

One of the key characteristics of Mexico City that affected the approach is that the metropolitan area (known as Zona Metropolitana del Valle de México, or ZMVM) has expanded beyond the administrative boundaries of the federal district and into the neighboring state of Mexico. For the most part, the main mass transport routes, such as the Metro, Metrobús BRT, and Red de Transporte de Pasajeros public buses, serve only the federal district and do not reach the entire metropolitan area. As a result, there is a significant underprovision of transit—especially rapid transit—at the urban periphery. This gap in service is filled by a vast network of privately operated microbuses, also known locally as *colectivos*, which carry 45% of trips and are the main mode of transport in the metropolitan area (*13*). Microbuses are the main feeder mode to the rapid transit network, with 67% of Metro trips, for example, originating from a microbus feeder route (*14*).

This has two major implications for the modeling approach. First, one would expect the terminal stations to have a disproportionately higher number of boardings compared with other stations, for they draw trips on microbuses from a very large area at the urban periphery. A quick overview of the data revealed that in Mexico City, BRT terminals had, on average 3.27 times more passengers than the average BRT station did, while Metro terminals had five times more riders than at the average Metro station. On this basis, one would expect a terminal dummy to be among the most important predictors of ridership for both systems. But there is also a concern that the terminal stations would be too different from other stations, owing to their unique circumstances, so it would be worth considering a model excluding terminal stations from the sample. The second implication is the difficulty in defining the catchment area of a station.

Station Catchment Area

Since most riders arrive on microbus routes (in the case of the Metro system; this information was not available for Metrobus) using a ½-mi catchment area as in the U.S. literature might not be accurate. The average duration of a microbus trip is around 36 min, and riders often transfer between two or more microbus routes before transferring to the Metro (*14*). On this basis, one would expect the actual catchment areas of Metro stations to be considerably larger than the standard 10- to 15-min walk commonly used in the literature. To address this issue, two variables were created to account for the catchment area. One is distance in meters to nearest station on the same line. This is a standard measure of catchment size, used in the literature (*1*). The second is station density—the number of other Metro stations within a 5-km radius. This is based on the assumption that given the length of trips on feeder routes, station catchment areas might overlap; one would therefore expect this variable to have a negative sign, since the presence of other stations in the vicinity might draw riders away from each station.

Network Connectivity and Ease of Access to Downtown

Another issue to consider is that if a passenger has the choice between multiple Metro or BRT stations within a comparably long microbus ride, he or she might choose the one that offers the best citywide connectivity and fastest access to his or her destination. One would therefore expect stations serviced by more than one Metro or BRT line to have higher ridership. Also, downtown Mexico City remains the main trip attractor in the metropolitan area (*15*). So it would be expected that stations with a direct line to the downtown to have higher ridership than otherwise identical stations that do not provide a direct connection to the CBD. Two variables were created to account for these aspects: one measuring the number of lines per station and a dummy for direct access to the CBD. Given the challenges related to the definition of catchment area, both of these variables would be expected to have positive signs and possibly to be better predictors of ridership than catchment size variables are.

Station Area Density

Since one of the main advantages of DRM models is their ability to capture the ridership benefits of smart growth, variables accounting for station area density are a key component of the models. This type of variable is meant to capture walk-on riders to transit stations, and therefore the foregoing discussion about the difficulties in determining catchment area for passengers arriving on microbuses is not relevant here. Density is usually measured for a ½-mi radius around the station, generally corresponding to the area from which most walk-on riders should arrive at the station. This is commonly done by creating ½-mi buffers around transit stations, overlaying them with census tract polygons, and then calculating population and employment density using geographic information system techniques (*2*). In the case of Mexico City, there was no access to a database of population or employment density at a resolution comparable with that of U.S. census tracts. Population density was available from two sources at the *delegación* level and the district level (*14, 15*), both of which are closer in size to U.S. zip codes than to census tracts, and they are in any case much too large to capture patterns in station area land use. There was an attempt to use delegación-level data for population density, employment density, and a combination of both but, as could be expected, none of them had any statistically significant impact on ridership.

To address this issue, a proxy variable was created for station area TOD that can best be described as an index of observed density of development around each station. This variable could take three values, ranging from 1 to 3 and representing, respectively, low-density, medium-density, and high-density development. There is a precedent for creating this type of variable in the context of travel demand modeling in a developing world context. The rapid demand assessment tools, described in the *Bus Rapid Transit Planning Guide* (*5*), include occupancy surveys of buses that use a similar set of indicators. Since the surveyors were not actually inside the buses for which they were estimating occupancy, and since they did not have time to do a full count of passengers, they instead created occupancy categories, such as full, three-quarters full, one-half full, one-quarter full, and empty. An important difference in the present case is that it is more difficult to define what medium density is, as opposed to observing that a bus is half full. An inevitable degree of subjectivity exists in this variable, and the aim was to address that by narrowing down the definition as much as possible. Therefore, the following definitions for low, medium, and high density are used:

- Low density. Some or all of the station area is developed, with buildings no more than two stories high and little or no mixed use. This is typical of residential areas away from downtown.
- Medium density. The entire station area is developed, with buildings of three to eight stories and a good mix of residential, retail, and other land uses. This is typical of most of the center city and some pockets of higher density development at the periphery.
- High density. The entire station area is developed, with a predominance of high-rise buildings (over eight stories high), or major trip attractors such as shopping centers, or both. This is typical of the core of downtown, especially along Paseo de la Reforma and Eje Central.

For the most part, allocating each station area to one of the three categories was fairly straightforward, based on observations during site visits, or by using a combination of aerial imagery and Google Street View. However, there were inevitably a few cases that did not fit squarely into one of the three categories. They were decided on a case-by-case basis. For example, the Dr. Galvez station on Line 1 of the Metrobús BRT features high-density office development and retail in the immediate vicinity of the station (3, or high density, according to the definition), surrounded by low-rise residential development in the ½-mile radius around it (1, or low density). Since labeling it high density would have overestimated the impact of land use on density, and labeling it low density would have underestimated it, the label given was medium density instead. Even though it does not fit in the definition of medium density as given here, it would be reasonable to expect a somewhat similar impact on ridership.

Microbus Routes

As noted, microbuses are the predominant mode of transport in Mexico City. Officially, microbuses operate under concession from the city government and are assigned to specific routes. But in practice, there is little oversight of microbus operators, and it is not known for certain to what degree they comply with the routes they are assigned. It is also possible that some percentage of microbuses may operate without a concession from the city, along undesignated routes.

The number of connecting feeder routes is one of the key variables used in DRM models to predict boardings at a given station, for it captures transfer passengers from other modes. In previous applications of the models in the U.S. context, the researchers relied exclusively on official data on number and frequency of connecting routes. In most developing world cities, using the existing data on formal transit routes may lead to underestimation of the actual number of transfer passengers at each station.

A variable was created for the number of connecting microbus routes, based on official statistics, but a quick overview of the data and a comparison with observed microbus traffic volumes at major Metro stations showed a discrepancy. The Pantitlán Metro terminal, for instance, has among the highest observed volumes of microbus traffic in the city, but it has only eight routes officially stopping there, just slightly higher than the systemwide Metro average of 5.4 connecting microbus routes, and considerably lower than stations, such as Oceania (22 routes) or Cerro de la Estrella (18 routes). Several factors can contribute to this, including unlicensed microbus operators and deviation from established routes; or perhaps the fewer routes at Pantitlán have a much higher frequency and demand than other routes do. In any case, this situation suggests that official statistics on microbus routes may not always be accurate, and a better variable to use would be microbus counts coupled with occupancy surveys.

Since station-by-station microbus counts were beyond the scope of this study, there was reliance on a proxy variable instead. During site visits to some of these stations, it was observed that stations with higher microbus traffic volumes also featured a microbus terminal—a series of parallel bays and platforms for microbuses, directly connected to the station. Therefore, a dummy variable was created for microbus terminals at Metro or BRT stations.

DATA SOURCES

Average weekday boardings for the Metrobus BRT system were provided by Metrobus. Disaggregate data on station level service attributes for Metrobus were computed from a 2010 operational review report on Metrobus, coauthored by Metrobus and the Centro de Transporte Sustentable de Mexico.

TABLE 1 Direct Model Estimating Daily Boardings at Metrobus BRT Stations on Lines 1 and 2

Variable	Coefficient	P
Number of connecting microbus lines	61.9	.662
Station area density (1 = low, 2 = medium, 3 = high)	3,120.6	.000
Connection to Metro (0 = no, 1 = yes)	2,510.1	.050
Terminal station (0 = no, 1 = yes)	8,759.3	.000
Catchment size [distance (m) to nearest station]	5.2	.008
Constant	−2,395.1	.234

NOTE: Number of observations = 51; $R^2 = .51$; F (probability) = 9.38 ($p < .001$).

Weekday boardings for Metro stations were obtained from official statistics published by the Metro de la Ciudad de Mexico for 2011. Calculation of the number of feeder bus routes connecting to each Metro station was done from bus route information published by the metropolitan transit agency for Mexico City, the Red de Transporte de Pasajeros del Distrito Federal, while the number of microbus routes was computed from information provided by ViaDF, a public online database of all transit routes in the city.

MODEL RESULTS

Terminal stations were the strongest predictors of ridership for the BRT model, as expected (Table 1). In particular, Line 1 terminals are the major access points to the city from the north and the south, and their ridership is much higher than at Line 2 terminals, which are not as close to the city edge. In the case of the Metro models, it was decided to exclude terminal stations from the sample. Given their considerable size and ultrahigh ridership (as many as 380,000 daily boardings for the Pantitlán terminal), they were obviously a strong predictor of boardings but would offer little other insight into the factors affecting ridership. In particular, since they usually have no BRT connections and low density around them, despite their high ridership, they might affect the coefficients and significance of the other variables. Therefore, the importance of terminals was acknowledged, but the two Metro models were developed without them (Table 2).

Catchment size, measured as distance to nearest station, was significant for the BRT (Table 1), but none of the catchment size variables developed for the Metro models were significant (Table 2). This is most likely because Metro stations draw riders via microbuses from an area so large that catchment areas actually overlap. This situation renders the notion of catchment sizes less relevant than the relative attractiveness of each Metro station in regard to network connectivity and direct connection to downtown. Both of these variables (number of Metro lines per station and connection to downtown) were highly significant (Table 2). Station area density was positively correlated with ridership and highly significant for both BRT and Metro systems across all the models (Tables 1 and 2).

The official number of microbus routes was not a significant predictor of ridership for BRT or for Metro outside the CBD (Tables 1 and 2), but it was significant for Metro within the CBD (Table 2). A possible explanation is that there might be better oversight and therefore better compliance by microbus operators within the CBD in regard to following designated routes. Therefore, the official number of routes better approximates the actual number of routes downtown. The dummy variable for the presence of a microbus terminal, however, was highly significant, at $p < .001$, as shown in Table 2.

PREDICTION ACCURACY

Accuracy of the DRM model's predictions can be evaluated by looking at the R^2-value and by plotting the predicted values versus actual boardings (*2*). The R^2-values in the models range from .51 to .54, toward the lower end of R^2-values found in the literature. This finding reflects the lack of good information on station area densities and connecting microbus routes, forcing reliance on proxies instead.

The 45-degree plot in Figure 1 shows that both the BRT and the non-CBD Metro model do a fairly good job of predicting ridership for lower patronage stops but tended to underestimate ridership for stations with the highest number of boardings, especially in the case of the BRT model. On a station-by-station basis, the predicted values fall, on average, within 32% of actual boardings for BRT and 48% for Metro. This finding confirms that the prediction value of DRM models is to offer order-of-magnitude estimates.

TABLE 2 Direct Models Estimating Daily Boardings at Metro Stations

	Non-CBD Model		CBD Model	
Variable	Coefficient	P	Coefficient	P
Catchment size [distance (m) to nearest station]	7.2	.178	—	—
Number of connecting microbus lines	305	.353	1,224.8	.002
Number of connecting bus and BRT routes ∗ dedicated lane (0–1)	981	.034	—	—
Microbus terminal present at station (0 = no, 1 = yes)	17,586	.000	—	—
Station area density (1 = low, 2 = medium, 3 = high)	8,909.4	.000	16,161.5	.000
Number of Metro lines at station	8,628.5	.049	—	—
Direct line to CBD (0 = no, 1 = yes)	9,390	.000	na	na
Long-distance train or bus station (0 = no, 1 = yes)	—	—	29,674.5	.044
Constant	−16,347.0	.050	−7,309	.349

NOTE: For non-CBD model: number of observations = 84; $R^2 = .54$; F (probability) = 12.87 ($p < .001$). For CBD model: number of observations = 41; $R^2 = .51$; F (probability) = 12.89 ($p < .001$). — = Variable not included in model. na = not applicable.

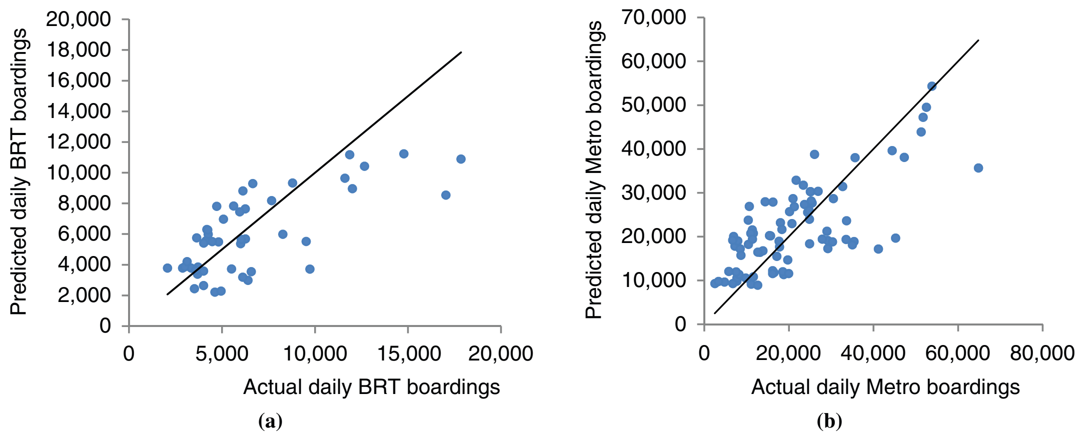

FIGURE 1 Plot of predicted boardings and actual boardings for (*a*) BRT system and (*b*) Metro non-CBD model.

POLICY INSIGHTS

While DRM models can be useful in providing rough ridership estimates, they are more useful in comparing different land use and transit service scenarios. As mentioned previously, some new transit systems, such as Metrobus in Quito or the Metropolitano BRT in Lima, Peru, had considerably lower initial ridership than had been projected (*6*). If that difference is high enough, it can create considerable financial difficulties for operators, and they will usually look for ways to increase ridership closer to initial projections.

A DRM model could be useful in such a case, by identifying the attributes that affect ridership and providing estimates of potential increases in ridership when these attributes are changed. For instance, the Mexico City Metro DRM model (Table 2) indicates that upgrading a station area from a low-density residential zone to a medium-density mixed use neighborhood can result in almost 9,000 additional daily boardings for that station. Rerouting five bus routes so that they connect to the station, and providing them with a dedicated lane, can result in up to 5,000 additional daily boardings per station, quite likely at a much lower cost than for redeveloping a station area.

Relationship Between BRT and Metro Networks

A key finding was the complementarity of the BRT and Metro networks. Stations that offered the opportunity to transfer between the two modes provided ridership benefits to each system, though this was measured differently for each mode. In the case of BRT, a dummy variable was used for connections to the Metro, since in most cases, BRT connected to only one Metro line (Table 1). In the case of the Metro model, an interactive variable was created, multiplying the number of bus, trolleybus, and Metrobus routes by a dummy variable for the presence of a dedicated bus lane (Table 2). While the total number of connecting bus and trolleybus routes was not a significant predictor of ridership for the Metro, the combination of connecting bus routes and a dedicated lane was. This relationship holds true for Metro outside the CBD and not within the CBD.

This finding suggests that the Mexico City government should prioritize efforts to improve intermodal transfers. The majority of transit users in Mexico City need to make at least one intermodal transfer to complete a trip (*14*). Yet the main transit modes in the city (Metro and BRT) are operated by different agencies and do not offer any integrated transfer facilities or fare integration.

TOD and Transit Ridership

Most transit stations in Mexico City do not have any TOD features. This study classified 71% of Metro station areas outside the CBD as low density, meaning that the predominant land uses were residential buildings of no more than two stories high. Since few people live within walking distance of these station areas, most trips on Metro or BRT involve taking a feeder route first. A common mistake made by planners in Mexico City is to concentrate efforts to increase ridership on improving connections to feeder routes, overlooking the potential to attract more walk-on riders.

However, the model results indicate that TOD interventions around both BRT and Metro stations can be effective policy for increasing ridership. Station area density was a highly significant predictor of ridership ($p < .001$), and results were consistent across all models (Tables 1 and 2). Upgrading a station area from a low-density residential zone to a medium-density mixed use neighborhood can result in an additional 3,120 boardings for a BRT station and as many as 16,000 for a Metro station within the CBD.

Given the underprovision of transit in the outlying areas of the metropolis and that some people switch between multiple microbus routes to reach the downtown, attracting high-density development near Metro stations would be a good policy for improving access to mass transport in the metropolitan area, by placing more people within easier reach of a Metro station.

CONCLUSIONS: APPLICABILITY OF DRM MODELS IN DEVELOPING WORLD CITIES

One of the main advantages of DRM models in the U.S. context is that they can use readily available public data on neighborhood attributes and station and service characteristics, and they do not need to rely on extensive data collection. One of their key strengths is their ability to capture the impact of station area population and employment density on transit ridership (*1*). However, this is possible in the United States given the availability of this information at a high level of resolution (e.g., census blocks and census tracts) through census data. The same is not true in most developing world cities. When census data are available, they are often at a scale considerably larger than the common definition of a station area. Also, given the rapid pace of urban development in the developing world, census data become outdated faster.

The DRM models as they are usually applied in the United States are still too data intensive for most developing world cities. It is rarely possible to create some of the common variables found in U.S. models, such as land use entropy (*1*), population and employment density within a ½ mile of a station (*1, 2*), or the frequency of feeder routes during the peak hour (*2*). This issue was addressed by using simplified versions of the variables (e.g., number of feeder routes instead of their frequency) or by creating proxies to replace variables where data could not be collected (e.g., index of density instead of actual density). The result is a watered-down version of a DRM model that still provides useful policy insights and has fairly good prediction accuracy, but a lower explanatory power. The models explained 50% to 54% of the difference in ridership between the different BRT and Metro stations. In the literature, U.S. models commonly had R^2-values in the .60 to .80 range, and occasionally as high as .95 (*1–3*).

The difficulty in accounting for informal transit is another drawback. Despite the fact that 67% of Metro trips originate from a microbus feeder route (*14*), the number of connecting microbus routes was not a statistically significant predictor of ridership for Metro stations outside the CBD (Table 2). This result is attributed to a high prevalence of informality in the microbus sector, including possibly unlicensed operation and deviation from established routes. A full travel demand model relying on a household travel survey is likely to address this issue better. Indeed, people will probably report trips on formal and informal transit with a comparable degree of accuracy in a survey.

Achieving the same degree of accuracy in DRM models in the developing world as in the United States would require considerably more data collection. Two key areas were identified where better data collection would likely improve the models: vehicle counts with occupancy surveys on informal transit routes, and obtaining more detailed information on station area density (e.g., estimates of number of housing units within walking distance based on building typologies).

Despite these limitations, DRM models show promise for developing world cities. With urbanization and investments in transit infrastructure expected to continue at a fast pace, developing world cities need fast and simple tools that can provide reasonably accurate estimates with minimum data requirements. Planners have adapted to this and have developed various rapid assessment tools and simple default values. In the case of ridership estimates, DRM models would represent a slightly more robust tool than rapid assessments, particularly useful in comparing how different land use scenarios or service configurations affect ridership.

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