URBAN TRANSPORT PLANNING AND MODELS IN LATIN AMERICA: PERSPECTIVES FROM THE CHILEAN EXPERIENCE

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AUTHOR'S PREFACE & ACKNOWLEDGMENTS

This work summarizes the author's ideas and opinions on the role and importance of transport models in the planning, development, and administration of urban transport systems in cities with characteristics like those in Latin America. These perspectives are the result of the author's experiences in working with urban transport models for the Chilean government in Santiago and other cities in Chile.

The principal objective of this document is to present the Chilean experience and to attempt to draw some lessons from that experience that may be useful in other Latin American cities and perhaps in other developing country cities. No experience is directly transferable from one reality to another; but, given the similarities in the problems and idiosyncrasies of Latin American cities, most likely some of the ideas and conclusions expressed here can be used by other transport planners and analysts faced with similar needs.

Finally, it is important to note that this document only discusses urban passenger transport. Although many of the ideas contained within are also valid for interurban transport and in freight transport, it is important to note the specific passenger context within which this document was developed.

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I. INTRODUCTION

1.1 In Latin America, urban transport problems must be viewed within the general context of developing countries, where resources are scarce and needs are many. Given this reality, the main objective of transport planning must be the optimal development and management of transport systems, within the economic and social constraints of the region. Because transport sector investments compete directly with other social sectors like education and health, these investments must only be made after a thorough examination of their cost-effectiveness from a societal point-of-view.

1.2 Currently, many of the principal cities of Latin America face serious problems in the operation of their urban transport systems. Although each city in the region has its own unique characteristics with varying degrees of challenges, the general trends throughout urban areas of the region are the same: growing levels of vehicular congestion and environmental pollution, deteriorating public transport service, increasing transport costs (fares, travel times, waiting times, energy consumption), poor general perception of the system by the users, etc.

1.3 As a result of these problems, the public is increasingly pressuring political authorities to take immediate actions. Unfortunately, the action most often taken translates into significant investments destined to expand physical infrastructure. Rarely are significant efforts made to optimize existing transport systems, despite the fact that such approaches can help realize large benefits at relatively low cost.

1.4 In general terms, the majority of transport investments focus on expanding road infrastructure and improving the movement of vehicles, primarily the automobile. Although public transport is by far the most important means of mobility in Latin America, investments are seldom aimed at exclusively improving the operation and service levels of this mode.

1.5 The one notable exception to the lack of focus on public transport is the large investments that some Latin American cities have dedicated to the construction of metro (urban rail) networks. Metros signify investments of several billion dollars even though their technical and economic justification is rarely clear and almost always subject to public controversy and ulterior political motives.

1.6 To summarize the challenges facing public authorities and urban transport analysts and planners in Latin America: on the one hand, current urban transport systems are facing grave problems and increasing complexity; on the other hand, transport solutions typically require large amounts of scarce resources.

1.7 A thorough technical, social, and economic evaluation of transport plans and projects is critical to successfully addressing the challenges in Latin American cities today. If such an evaluation is inadequate, then the investments that are made will also be inadequate, the problems that were intended to be addressed with the investments will not go away (indeed they may only intensify), and precious resources which are urgently needed in other sectors of the economy will be squandered. Avoiding shortcomings in program evaluations requires that attention be focused on the range of tools utilized for studying and assessing plans and projects. Within the broad array of these tools, transport models play a fundamental role.

1.8 Models are basically used to simulate the operation of a transport system during a given period of time (i.e., peak period) in distinct scenarios. Typically, one scenario represents the actual operation of the system and another scenario represents the operation of the system after the introduction of a new transport project. By comparing both situations (with and without the project), it should be possible to calculate the benefits associated with the project and weigh them against the respective costs of the project to determine the social economic rate of return.

1.9 The capacity of transport models to adequately "model" or simulate the transport system is a decisive factor for the purposes of evaluation and, in turn, the investment decisions made based on that evaluation. Generally, it is fair to say that better models will drive better decisions and that poor models could result in gravely erroneous decisions. Since these decisions normally signify large investments, the models used play a crucial role in this process.

1.10 Nearly all transport models used in Latin America (when used at all) were initially developed in Europe or North America. Unfortunately, these models are not always adequate in the Latin American context, either because their fundamental hypothesis is not realistic to Latin America or because Latin American transport systems present characteristics which these models were not designed to handle. This document analyzes the shortcomings in these models, efforts made to overcome these shortcomings, and the challenges still remaining. This document will also discuss some problems directly related to transport -- the environment and land use -- which are of concern in Latin America and that present additional requirements to transport modeling.

1.11 Before exploring further the subject of modeling, the next section will discuss, in brief, transport policies. In practice, these policies define the reality of transport planning and decision-making and, consequently, define the requirements and the contexts within which the models work.

II. TRANSPORT POLICY AND MODEL REQUIREMENTS

2.1 Traditionally, the administration and development of urban transport systems in Latin America have been undertaken with policies and strategies imported from industrialized countries. The basic premise of these policies has been infrastructure expansion as the principal, and at times only, response to pressures on the system imposed by increased economic activity and growing urban populations. In the majority of cases, infrastructure expansion is aimed basically at improving the traffic flow conditions for the private automobile.

2.2 For a variety of reasons, this policy is clearly inconsistent with the reality of Latin American countries. First, giving priority to automobiles reflects general confusion with respect to the final objective of the urban transport system -- the need to satisfy the movement and transport of people, not vehicles. This difference, subtle as it may seem, is very important in the Latin American context, especially given the typical modal split in the region: 20%, or less, of the daily motorized trips are done by automobile and 80% are done by public transport. Despite the overwhelming number of trips fulfilled by public transport, the majority of vehicles operating in the system are automobiles.[1] Furthermore, non-motorized trips (pedestrians, bicycles, and animal traction) represent a third or more of total daily trips (SECTRA, 1991).

2.3 The expansion of road infrastructure exclusively dedicated to improve the operating conditions for automobiles, benefits a limited number of users and has a minor impact on the overall operation of the system and its objective of transporting **people**, especially considering the modal splits in a typical Latin American city. In addition, this approach has several other disadvantages, including:

- It involves high costs. The continuous expansion of road infrastructure imposes financial costs that cannot easily be met in the majority of Latin American countries.

- It provides incentives for automobile use and dependency at the expense of public transport use, causing the latter mode to be decreasingly profitable for operators. Operators, then, must respond by lowering the quality of public transport service, raising fares of service and/or pressing for operating subsidies.

- Most importantly, it fails to provide a sustainable solution. International experience shows that the continued expansion of auto-oriented road infrastructure will not only fail to solve the problems of transport, but will also, in the long-term, aggravate them. This is particularly true in the presence of vehicular congestion. New infrastructure may temporarily alleviate the congestion (depending on the level of latent demand), but the better operating conditions for the automobile -- and its subsequent attractiveness relative to other modes -- will increase demand for automobile travel, raising again the level of congestion in the system.[2] As a result, in the long run, system performance degrades, but this time the magnitude of the problem is greater because there are more automobiles in the system.

2.4 An appropriate policy for urban transport in Latin America should, first and foremost, begin with a change from a purely "infrastructural" approach towards an "integral" approach. The urban transport system should be analyzed as a true "system," the operation of which results from an equilibrium between transport supply and demand.

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[1]For example, in Santiago 400,000 automobiles carry about 1.4 million daily trips, while only 12,000 buses carry about 4 million daily trips (SECTRA, 1991).
[2]The phenomena of infrastructure inducing more demand, known as convergence or "the fundamental law of traffic congestion," is well-documented in industrialized countries (see, for example, Downs, 1962; Downs, 1992).

Within this integral approach, infrastructure is only one of the many system components; other supply and demand components also exist which, together, explain transport system behavior. These elements must be considered together in order to properly study the problems and potential solutions.

2.5 Additionally, a Latin American-focused urban transport policy should aim to find solutions that are appropriate for the unique problems of cities in the region. Such a strategy will require significant efforts to identify and understand the distinct nature of these problems and to develop or adapt the tools for technical analysis which can most effectively handle the reality in Latin America.

2.6 From the above discussion, it becomes clear that a Latin American urban transport policy should have at least the following objectives:

- Priority for public transport as the primary transport mode;
- Internalization of the real costs of transport for system users.

Public Transport Priority

2.7 Given that the majority of transport users in Latin America today ride public transport and very few have alternative options (because relatively few have access to an automobile), implementing policies that prioritize public transport is still a politically feasible strategy. However, as economies in the region continue to develop and personal disposable incomes increase, the number of automobile owners in the population will also increase, which will make it increasingly difficult politically to implement public transport prioritization. Increasing motorization rates, combined with a deficient public transport system, threatens to drive many cities in the region into a downward trend that is common in most of the world's cities: as public transport service declines, more and more users try to switch to the automobile; the cycle accelerates as public transport demand reduces, service further worsens, and demand for auto travel continues to rise. Even a small increase in the number of autos in most Latin American cities will be enough to begin this cycle and bring transport systems to the brink of collapse.

2.8 Stopping the process of permanent decline in public transport service requires the adoption of measures that give priority to this transport mode. In practice, public transport priority measures include: giving exclusive or prioritized rights to buses on the existing road network (i.e. through bus lanes, traffic signal priority), constructing road infrastructure especially for surface public transportation, introducing mass transit systems in corridors where demand justifies it, and improving and diversifying public transport service to better satisfy the distinct characteristics and requirements of different user categories.

2.9 From a technical point of view, public transport is not only more efficient in terms of roadspace, energy consumption and emissions per passenger transported, but it also is cheaper and probably the only affordable alternative in the long term for the majority of

Latin American cities. From a social perspective, public transport prioritization is clearly redistributive in that it tends to favor the lower income segments of the population, providing them with better quality transport service (in terms of travel times, wait times, and fares) and increased accessibility and mobility for improving work, social, shopping, and other transport-related opportunities.

Internalizing Costs

2.10 A Latin American-specific transport policy should also work towards **internalizing real costs**. This requires that transport system users pay for the external costs that their travel decision imposes on society. Two typical transport externalities -- congestion and pollution -- are responsible for the major problems facing urban transport systems in Latin America today. If the costs perceived by the users do not equal the real full costs that user decisions imply, then the costs will induce user behavior that is socially inefficient and expensive. In essence, society is forced to cover the difference between the real and perceived costs, representing a subsidy.

2.11 This difference, which essentially represents a market distortion -- well documented and analyzed in technical literature -- requires some means of reconciliation, a method of reducing the market imperfections and showing users the full costs of their decisions. The most commonly recognized solution for overcoming the market inefficiencies resulting from the existence of externalities in transportation is road or urban area pricing. Road or area pricing attempts to display to users the full costs of their decision to drive and to send the economic signals necessary to get users to make more socially optimal choices. Although theoretically advocated by economists and transport engineers, road pricing presents a complex political challenge because it forces users to pay more for a good they previously consumed at little cost -- an unpopular measure. The issue is further complicated, especially in Latin America, because it primarily affects the most influential segments of society, those that own automobiles.

2.12 Despite the obstacles to practical implementation of road pricing, it remains clear that, in the long term, no transport policy will succeed without taking the necessary measures to, in some way, correct the natural transport market distortions -- in other words internalizing the external costs of transport and driving the agents involved in system operation (the users and operators) towards more rational decisions from a societal point of view. By internalizing the costs, other transport policies will be more effective. For example, public transport prioritization will have more of an impact on user choices when combined with a policy of road pricing, because public transport use will become even more cost-competitive with auto use. Also, fully internalizing transport costs, by eliminating excess travel demand produced by inefficient market signals, will help reduce the pressure to build more road infrastructure. Both of these results are very desirable to Latin America.

III. TRANSPORT MODELING

3.1 Regardless of the specific approach adopted, a transport policy will result in projects and plans which should be studied, analyzed, and evaluated along the lines of the desired policy objectives and within financial, economic, and social resource restrictions. Normally, the projects and plans are developed into a program of medium- and long-term investments.

3.2 To do the necessary technical and economic analysis and to study and compare the potential impacts and limitations of the alternative options proposed requires a capable transport model. The technical requirements of such a model are defined by both the characteristics of the transport system and by the objectives that a specific transport policy intends to achieve.

3.3 The role of models in the process of transport planning is to simulate the operation of the transport system under diverse scenarios. The basic scenario -- the base case -- is the actual existing transport system in the city and the alternative scenarios are those defined by the introduction of new transport projects or plans that will alter the functioning of the system. By comparing the operation of the transport system in two distinct scenarios, it is possible to quantify the changes produced through the introduction of new plans and projects and, in this way, it is possible to calculate the eventual benefits of the different proposals.

3.4 Transport projects and plans are of diverse categories, ranging from infrastructure expansion projects (Metro lines, street widening, new urban freeways) to system and demand management projects (road or area pricing, dedicating bus-only lanes). The introduction of new projects will impact the operation of the system, hopefully resulting in benefits such as time savings, vehicle operating cost savings, and air pollution reductions. Quantification of these savings is critical for fairly evaluating the different projects and determining the economic rate of return on the financial investments involved.

3.5 The task of quantifying project benefits is directly related to the capacity of the models to adequately simulate the operation of the transport system, given certain transport supply and demand conditions. The introduction of a transport project will basically change the characteristics of system supply, demand, or both. For example, a new Metro line or the construction of a new urban freeway represents a typical modification of the system's supply characteristics because such options are offering new travel alternatives for system users (at least for some of the users). Street widening, the establishment of bus-only lanes, and other initiatives also represent supply modifications. In contrast, initiatives such as road pricing or fuel taxation change the characteristics that define transport demand. The basic question that models should respond to is how will operation of the transport system change as a consequence of a modification of the system's supply and/or demand characteristics.

3.6 In practice, the characteristics of transport system supply and demand are intrinsically linked and inseparable. The number of users traveling between an origin/destination pair on a certain transport mode and with a determined trip purpose (transport demand) is intimately linked with the operating conditions (transport supply) that the users encounter in the transport network. The reverse of the relationship also holds true: the operating conditions in the transport network are a consequence of the number of users that utilize each network, that is to say, the demand that each mode faces.

3.7 This intrinsic relationship between transport supply and demand implies that system operation results from an equilibrium between both, and -- given that both influence each other mutually -- it is not possible to analyze demand separately from supply. This consideration has important consequences for transport models and introduces one of the principal technical complexities relating to modeling. The primary objective of transport modeling is to find the equilibrium in the system, both in the existing system operation as well as in the hypothetical operations that will be produced with the introduction of new transport system plans and projects.

3.8 Basically, a "good" transport model should, on one side, correctly predict the number of trips between each origin destination in the city in each transport mode in the city (demand prediction). On the other side, the model should correctly determine the flows and operating costs in each of the links of the distinct transport networks (supply prediction). But, the operating costs in the networks should be consistent with those costs used in predicting the trip demands in order to guarantee that a **state of simultaneous supply-demand equilibrium** in the system is reached.

3.9 The difficulty in finding the equilibrium state in the transport system stems from the intrinsic relationship between transport supply and demand, which impedes a separate analysis of the two. To further clarify this point, it is necessary to briefly revise the fundamentals of the transport model.

3.10 Since transport system operation varies greatly during the day, normally certain representative periods of the day are chosen to try to simulate the system. Typically the analysis is done separately for peak travel periods (rush hour) and non-peak periods. Supposing that an area of a city is divided into a group of zones that represent the origin and destination points within a determined analysis period, then transport demand during that given period (for example, the morning peak period) can be expressed in three basic questions:

1. How many trips originate in and are attracted to each zone **i** in the city? (trip generation)
2. How many trips are realized from zone **i** to zone **j** in the city? (trip distribution)
3. How many trips are realized using transport mode **m** to go from zone **i** to zone **j**? (Modal split)

3.11 The answer to the first question is related to land uses within each zone of the city. The number of trips generated and attracted in each zone is explained by the different urban characteristics of that zone (residential, commercial, industrial, etc.) and by the socio-economic characteristics of the people that live there or travel there for certain purposes (work, study, shop, etc.). In other words, in the short term, the number of trips that are generated and/or attracted in each zone is not related to the operating characteristics of the transport system. Due to this fact, the majority of transport system evaluations considers that, **in the short run**, trip generation is constant.

3.12 In the **long run** however, the transport system both has influence over land uses and is influenced by land uses -- the operating conditions of the transport system can induce changes in land uses and the changes in locations of homes, offices and industry has impacts over the operation and development of the transport system. Since transport projects are long-term in scope, it is clear that, in some way, future trip generation will be influenced by the evolution of urban land use patterns.

3.13 Unfortunately, despite research efforts currently underway in many areas around the globe, the direct relationship between transportation and land uses remains unclear both in theoretical and practical terms.

3.14 One possibility for working with the current difficulty in predicting the long-term interactions between land use and transportation is utilizing the technique of future land-use scenarios to deduce future transport demand. This technique consists of defining a group of "*possible land uses*" that have a certain probability of developing in the future, and then evaluating future transport projects within the context of the different land use scenarios. This scenario technique is commonly used in countries like Chile, but the option of including the more synergistic relationship between land use and transportation as part of the transport modeling process in Chile remains open.

3.15 Land use is not the only important variable in trip generation. The socioeconomic characteristics of the users of the transport system also play a major role in determining the number of trips generated and attracted to each zone. Among these characteristics, two variables are especially important: personal income and availability of the automobile. Accounting for these variables requires predictive models that can estimate these two variables in the future. This introduces additional degrees of uncertainty in transport modeling. In Chile, as in most of the rest of Latin America, motorization growth rates are strongly correlated with growth in personal income. Typically, the operating conditions of the road network and other transport system characteristics have little influence in the decision to buy or not buy an automobile when a certain income level is reached by the individual.

3.16 The two following questions that define transport demand (trip distribution and modal split) are analyzed through mathematical models, that require knowledge of the operating costs for each transport mode available to users between each pair of origin destination zones.

3.17 Trip distribution models typically utilize models derived from entropy maximization theory. To determine how many trips will occur between zone **i** and zone **j**, these models require estimated operating costs (monetary costs, travel times, waiting times) for all available travel modes between the two zones. The trip distribution model results in a trip matrix for each pair of origin-destination zones.

3.18 In the case of modal split, the demand for **each transport mode available to go from zone i to zone j** is explained by the operating cost (among other variables) of each transport mode. To do this, logit models, which define a group of alternatives that represent the modes available to the user, are typically utilized. Each alternative is associated with a utility function, which includes the corresponding operating cost variables as well as other variables relevant to the user. The modal split model results in a matrix of trips between origin-destination pairs by each transport mode.

3.19 After the trip matrices for each transport mode have been determined (demand), these trips need to be assigned to the network for each mode using trip assignment models, also known as supply models. To simplify the discussion of assignment models, only two transport modes will be discussed here: private transport and public transport. Assignment models need to be divided into two groups since trip assignment to the private transport network is completely distinct from assignment to the public transport network. In Latin America, public transport assignment, because it carries a high relative portion of trips, deserves very important attention.

3.20 The strongest **private transport** assignment models use Wardrop's first principal to explain trip assignments in the network. Wardrop's principle assumes that users try to minimize their operating costs on their trips. If possible, each user would elect the shortest route (in terms of travel time, for example) to arrive at his/her destination. But, given the phenomena of vehicular congestion, the shortest route stops being the route of choice as soon as many users try to utilize the same network arcs. Users, therefore, will begin to consider other routes until finding that which has the minimum possible cost, given the existing operating conditions in the network. When all users have found the most convenient route, the private transport network arrives at an "equilibrium" state[3] (Van Vliet, 1976). Wardrop's first principal simply says *that there will be "network equilibrium" when no user can unilaterally reduce his/her travel cost through a change in route* (Wardrop, 1952).

3.21 The presence of vehicular congestion complicates the determination of network equilibrium. The cost of travel in one determined network arc depends on the traffic flow in the arc; consequently, the more users on an arc, the more congestion on that arc, and the greater the costs for the users. Since users utilize a group of connected arcs to travel between an origin and destination, the total cost of the trip will be the sum of the costs that the user encounters in each of the arcs traveled. Clearly, many arcs in the network are used by many users for many origin-destination pairs so that, in the end, the travel costs between any single origin-destination pair depends in the demand existing between all pairs in the city.

3.22 **Public transport assignment** faces a problem completely different from private transport assignment. For public transport, users elect a bus line (or Metro line or any

[3] It is important not to confuse this concept of network equilibrium with the concept of transport system supply-demand equilibrium that was discussed earlier.

other public transport mode that is being studied) for their trip. In this case -- given that the bus lines are fixed routes on the network -- the users do not make their decision based on the road network (as the automobile drivers do), rather they decide based on the various public transport lines available to make the trip.

3.23 The distinct hypothesis that defines how users select the public transport line for their trips shows the need for different assignment model for public transport. Most traditional models assume that the user will select that specific line which minimizes "total travel time" (which normally includes a combination of fare, waiting time at stops, and travel time in the vehicle). Clearly, this traditional working hypothesis is correct if a user only has one available line or a small group of very different lines (in terms of varying travel times, wait times, fares) available to realize a trip. In that case, it is reasonable to assume that the user will select that line which minimizes total travel time. These type of models are known as **assignment to minimum schedules.**

3.24 In Latin America, however, where public transport carries the majority of urban trips, normally the number and coverage of available lines is very large. Consequently, users can often access a group of similar lines (again, in terms of fare, travel time, wait time) for any given trip, so that the hypothesis for selecting from only one line is not adequate. In reality, users can choose from a subgroup of similarly attractive lines, with the aim of **minimizing "total expected trip time."** For any given trip, the user will choose a line from this subgroup.

3.25 Once this working hypothesis (related to the user's behavior in line selection) has been established in mathematical terms (Chriqui and Robillar, 1975), it is possible to formulate models that assign public transport trips much more realistically for the actual operating conditions of this mode in Latin American countries. Such models are known as **assignment to minimum public transport routes** (De Cea and Fernandez, 1989). The development of these types of models is of utmost importance in Latin America -- where public transport plays such an important qualitative and quantitative role in the region -- because the traditional assignment model is inadequate.

3.26 Other models also exist (like that based on the concept of **minimum public transport strategies** (Spiess and Florian, 1989)) which assign public transport trips with results that are very similar to the minimum route assignment.

3.27 An additional difficulty to effectively modeling public transport stems from the presence of congestion, which has two dimensions in public transport. First, vehicular congestion affects buses' travel time in the same way that it affects auto travel times. If automobiles and buses compete for the use of the same roadspace, then the costs to public transport users (their travel times) will be influenced by the vehicular congestion produced by autos (and vice versa). A second form of congestion in the public transport system results from the capacity restriction of the buses. Since buses do not have an infinite capacity to carry all passengers that want to use them, there exists the chance that a user might not be able to board a bus at a given stop and will instead need to wait for the next bus that serves the desired trip. In this case, the user will see an increase in waiting time and, accordingly, an increase in total travel time (De Cea and Fernandez, 1993).

3.28 Both vehicular congestion and capacity restriction in the public transport system are very real phenomena in Latin America's urban transport systems. So, to be realistic, public transport assignment models should be capable of effectively handling both situations.

IV. TYPES OF MODELS

4.1 Regardless of the specific assignment models used, both for public and private transport, it remains clear that operating costs for each transport link are only known **after** the trip matrices from the demand estimation have been assigned to the networks. Only then is it possible to establish the estimated flows in each link and, therefore, the travel costs in that link. But, as mentioned earlier, to estimate demand requires knowledge of the travel costs between each origin-destination pair. In order for the technical analysis to be consistent, the costs used in estimating demand should be the same that result from assigning this demand to the network.

4.2 Transport models, such as the traditional Sequential Transport Model (the four-step) do not always fulfill this need for internal cost consistency. The Sequential Model is based on a consecutive analysis of Generation - Distribution - Modal Split - Assignment in which the outputs of each stage serve as inputs for the following stage. In this model, there does not exist a guarantee that the costs utilized in the demand stages are consistent with those resulting from assignment. This inconsistency worsens as congestion levels in the network worsen.

4.3 If a model lacks consistency in the internal costs used, the model will not find the system supply-demand equilibrium and will produce unrealistic results. Such inconsistency can be reduced if the costs utilized in demand estimation are measured directly from the actual links. In that case, the model will probably perform better in simulating the actual system operation because the assignment models should assign each arc with the traffic flow corresponding to true operation and, as a result, the costs should be basically similar to those utilized in estimating demand.

4.4 Nevertheless, models are not designed to simulate the current operation of the transport system; rather the crucial objective of models is to simulate future hypothetical operations of the system that might result from the introduction of strategic transport projects. Such projects will eventually modify demand and the subsequent assignment of trips on network links, on which the costs will also vary and in which case it will not be possible to measure them from a *reality* that does not yet exist. For example, the introduction of a new Metro line in a city will likely take a good number of trips from the road system which will produce route reassignments and new costs for the users that continue using the surface transport system. If the model cannot capably predict the new costs it will not be capable of finding the new equilibrium state in the system after introducing the new Metro line.

4.5 The above discussion intends to show that even if a sequential model can eventually replicate the currently operating transport system, there is no guarantee that the model will correctly simulate future system behavior after strategic modifications are introduced. These shortcomings become more pronounced as larger system changes are considered and as congestion worsens.

4.6 To overcome the cost inconsistencies between the supply and demand stages in the sequential model, an iterative process can be used. In other words, a first iteration of the model estimates the demand and assigns the resultant trips to the network links, thereby obtaining new cost figures. In a following iteration, the sequential model re-estimates demand using the costs from the previous iteration and reassigning the new trip matrices to the respective networks. Unfortunately, this iterative process does not guarantee a convergence of supply and demand; in fact, experiences with the iterative process in Chile have shown that when congestion is especially high, this iterative process diverges and produces very unreliable results.

4.7 Despite the well known theoretical and practical problems of the classical sequential model, this model continues to be the most commonly utilized transport model in both the developed and developing world. For the developing world, including Latin America, widespread application of the sequential model can result in incorrect conclusions and gravely erroneous investment decisions.

4.8 A second generation of transport models, developed in large part during the 1980s, is known as the **Simultaneous Supply-Demand Equilibrium Model.** This model is intended to overcome the cost inconsistencies present in the traditional sequential model. To simulate transport system operation, the simultaneous model formulates a problem of variational inequalities that has mathematical characteristics that require the use of solution tools like diagonalization. This solution technique consists of an iterative process: in each iteration a mathematical optimization problem is formulated and resolved, subject to certain restrictions that reproduce the transport supply and demand conditions (Fernández and Friesz, 1983). In this way, the model simultaneously resolves the stages of transport supply and demand, finding a solution in terms of trip matrices by mode and traffic flows over links in the network that are internally consistent -- the costs used to estimate demand are the same costs that result from assigning this demand to the links. In other words, by resolving the problem of variational inequalities, the model finds the supply demand equilibrium.

4.9 Among the most notable real-world applications of this model is of Santiago, Chile (Fernández and De Cea, 1990) where the model has been used extensively in the last five years to study a large number of strategic transport projects, including extension of the Metro network, additions to the road network, and public transport projects. These infrastructure projects signify investments of several hundred million dollars.

4.10 The Chilean version of the equilibrium model known as ESTRAUS (SECTU, 1989) simultaneously resolves the two stages of demand (trip distribution and modal split) and supply (network assignment). Trip generation remains outside the transport model because of the difficulties mentioned earlier with predicting interactions between land use and transportation; instead, the model uses the technique of different land-scenarios used.

4.11 The model considers for each analysis period (a.m. peak and off-peak): 11 transport modes, 12 classes of users, three trip purposes, and 270 traffic analysis zones (TAZs) in the city. The distribution stage of the process uses entropy maximization models. The modal split stage uses multinomial logit models and hierarchical logit. Private transport assignment uses the model of Frank Wolfe to find the Wardrop equilibrium and public transport assignment uses the model of assignment to minimal routes.

4.12 In ESTRAUS, the definition of the demand model is not rigid. In other words, both the distribution and modal split submodels can be replaced with models that are theoretically and practically improved. For example, the Logit model for modal split can be replaced with a Probit model, but the mathematical complexity of the latter currently makes it inadequate for practical application. Indeed, the demand models within ESTRAUS are improved each time that they are recalibrated with new and better information.

4.13 Although currently ESTRAUS only considers two analysis periods (peak and off-peak), this is not a limitation of the model itself; rather it reflects a limitation in current data availability. It is important to remember, that each additional analysis period (i.e. evening peak) requires calibration of the specific demand models and the definition of specific inputs (trip generation).

4.14 Perhaps the most important limitation of ESTRAUS in its current version relates to its inability to manage multipurpose, or "chained," trips. Although currently chained trips represent a small portion of trips in Santiago, this will likely change in the future. To address this phenomena, efforts are underway to make ESTRAUS better simulate trip chaining.

4.15 Although the simultaneous equilibrium model has drawbacks and limitations, it represents significant advances over the classic sequential model. Despite this apparent technical superiority, however, most cities of the world -- including those of North America and Europe -- continue using the sequential model. Widespread use of the sequential model has continued because of several forces, including:

- Sequential models, despite their shortcomings, have been in use for decades with little criticism because until recently they were the only available tool for transport analysis. In fact, almost all commercial models and software programs available on the market use the sequential process.

- Simultaneous equilibrium models are relatively new and are more mathematically complex. Although not of concern to the decision-makers who only need the model outputs, the increased model complexity places greater capacity needs on technical personnel and therefore will likely produce a certain resistance to acceptance.

- The advantages of a better model are strongly linked to the need for thorough transport project evaluation. In turn, the requirements for thorough evaluation is strongly linked to the relative scarcity of financial resources available for transport investments. If resources for transportation investments are abundant, then it may be possible that rigorous models are not *as* critical. But, in the case of Latin America and most other developing regions of the world -- where financial resources are very scarce -- the quality of models is critical for making adequate investment decisions.

4.16 Beyond the sequential and the simultaneous equilibrium models, a third generation of models, called **dynamic transport models** (Fernández and De Cea, 1993), deserves mention. Dynamic models introduce time variables into the analysis, attempting to simulate the transport system minute by minute, with the objective of studying with much more detail the behavior of certain transport variables. Along with potentially providing for more accurate transport system performance, dynamic models allow for analysis of related problems, such as real time computerized assistance for route selection. Dynamic models also might prove useful for improving analysis of transport impacts on air quality, noise pollution, and energy consumption.

4.17 Nevertheless, dynamic models still remain a research agenda item and only an eventual practical possibility. These models involve mathematical formulas that are much more complex than static (sequential and simultaneous) models and raise a large number of questions and problems that remain without a theoretical solution. Due to these barriers, dynamic models will not be practical analysis tools in, at least, the medium term. Whether such models will have an important impact on transport analysis in Latin America remains unclear.

V. LIMITATIONS IN TRANSPORT MODEL APPLICATIONS

5.1 The limitations in the application of transport models can be differentiated into two categories: theoretical and practical. Among the theoretical limitations, the most important have been discussed in this paper and relate to the actual capacity of available models to help study and resolve transport problems. The practical limitations relate to the difficulties of actually applying the models and using their outputs within the Latin American context.

5.2 One of the primary theoretical shortcomings of modeling has to do with the relationship between land use systems and transport systems -- specifically, the exact nature of this relationship and its implications for transport analysis. As discussed earlier, land uses influence trip generation and the transport system induces certain changes in land uses. But, effectively modeling where and how these mutual influences occur still remains open to significant research.

5.3 Commercial models do exist which propose solutions to the transport/land use link, for example by adding a fifth land-use submodel as the first stage in the sequential model. But, these types of models lack clear theoretical and analytical foundation and their results are often subject to much criticism. Part of these criticisms point at the difficulty in predicting the long-term traits of a very complex land use system, the future evolution of which depends on many variables, only one of which is transportation. Essentially, analytical tools do not yet exist that can forecast with confidence what a city will look like in a 10 or 20 year timeframe. The dynamism of urban development remains too complex. Adding the need to know the impact of transport system changes on the future evolution of cities only further increases the complexity.

5.4 In Latin America, the discussion takes on more than theoretical challenges. Many cities in the region are currently in a state of rapid, unrestrained growth, which makes their medium and long term form very unpredictable. Even when authorities directly intervene in urban growth, attempting to manage and direct it, the results remain difficult to predict. The socioeconomic characteristics in most Latin American countries, driving many lower income segments of the population to migrate to cities and settle on the urban outskirts, also strongly influence urban development.

5.5 From a transportation perspective, the often random development patterns of the typical Latin American city makes it extremely difficult to concretely predict the impacts that transport projects could have on urban form. Given this fact, it would be very risky to justify transport projects based on the potential positive impacts that such projects might have on land uses. For example, in Santiago Chile, experience shows that the construction of the Metro -- a very important transport initiative in the city -- has had mixed effects on land uses in the city.

5.6 Another current limitation in transport analysis (at least in Chile), relates to the effective modeling of the environmental impacts of transport projects, the benefits (or costs) of which are currently not considered in evaluations. This limitation can and should be overcome soon because quantifying environmental impacts of transportation is becoming increasingly important in most major cities in the region. In Chile, the currently available transport model (the simultaneous equilibrium model) can produce, with enough confidence, traffic flows and average speeds in each link in the network. Using emissions factors from a mobile source emissions model (i.e. U.S. EPA's MOBILE model) the "average speed" outputs along with other data that ESTRAUS can also provide (such as average trip distance, percentage of each type of vehicle in each link of the network, etc) can be used to generate vehicle emissions for the transport system.

5.7 With this data it is possible, in principle, to develop environmental analysis (in air quality terms, for example) that would allow for the quantification of benefits that a given transport project or set of projects will produce. These quantified benefits can then be integrated into overall project evaluation. Despite these strong possibilities, efforts to actually integrate environmental analysis into actual project evaluation have only begun (at least in Chile) and certainly this remains a field of great potential in the near term.

5.8 It is also important to recognize that the "average speed" emissions estimates of ESTRAUS, like all other static transport models, still only offer rough estimates of system vehicular emissions. Indeed, actual vehicle emissions depend more heavily on actual driving patterns, such as stops and starts and accelerations and decelerations. To more accurately measure vehicle emissions will require moving away from average speed models towards more detailed network assignment procedures which can provide more that average link speed estimates. Such model development is the focus of intense global research today.

5.9 As far as road pricing is concerned, a static model can study with relative ease the transport system impacts of introducing a price to enter an area of a city or a certain road in a city -- as long as the imposed price is a single fixed cost (a simple toll). This case simply requires a modification in the cost function of the links connecting the priced area or road by introducing into the model the corresponding fixed cost.

5.10 Although being able to model fixed cost pricing schemes is useful in terms of transport policy analysis, it does present certain limitations. Static models, by nature, can only account for fixed (or constant) price schemes in each of the affected links. Ideally, however, the transport planner will want to analyze the impacts of a variable pricing scheme, one in which the cost of entry (into the area or road priced) varies with time of day or level of congestion (or even occupancy of vehicle). For example, a road charge does not only depend on the entrance into a restricted area, but also the time during which the user remains within the area. Given the fact that static models do not account for changes in time, they are not adequate for simulating these variable costs. Most likely, modeling variable pricing schemes will require the application of dynamic models.

5.11 Among the practical shortcomings of transport modeling application in Latin America, data and information requirements must be mentioned. This report has focused on transport models in relatively abstract terms but the calibration and validation needs of these models represent an important additional challenge in terms of both technical capacity and data.

5.12 A transport model requires a large volume of data for calibration and validation. Typically, this data comes from surveys designed specifically for estimating travel demand and the nature of that demand. The most common forum of survey is the origin-destination (O-D) survey, normally conducted by interviewing people that represent sample demographic segments within a given travel area. The survey can help determine specific travel patterns in the study area, whether that area be a single neighborhood, a subdivision, a commercial development, or an entire metropolitan area (Kell, 1992). Means of conducting such surveys vary, ranging from direct interviews in homes, phone interviews, mail surveys, or some combination. Other information needs that also are necessary to transport modeling and complementary to O-D surveys include traffic counts, cordon counts, vehicle occupancy counts, transit inventories, etc.

5.13 Although the size of the sample household survey and the number of questions asked varies from city to city, the technical design (and financing) of an O-D survey is very important. For example, in Chile, as part of the development of ESTRAUS, relatively comprehensive O-D surveys were conducted. When ESTRAUS was first developed in the mid-1980s, it was calibrated with limited data available at the time. In 1991, a thorough O-D survey was conducted, covering a total of 33,000 households (3.3% of the city's households) at a cost of nearly US$ 1.3 million. The time necessary to design the O-D survey and collect, process, and validate the data was 18 months. After finishing the 1991 O-D survey, recalibrating the model took approximately 12 months.

5.14 Relative to the amount of money and effort spent in constructing transport projects, data collection comprises a small portion of expenditure. However, data collection requires investments that are not easily justified to political authorities and the general public, because in and of itself, data does not produce a "new" facility. Failure to collect adequate data, however, will result in modeling and transport analysis efforts which will be, at best, subpar. The quality and integrity of data used to calibrate, validate and operate a model are as important as the quality of the model itself; therefore data collection must be considered an integral component of any transport study. Once a model has been successfully calibrated (ideally with the data from an O-D survey), additional data needs to maintain an accurate database are easier and cheaper to acquire (for example, through traffic counts, motorization rates, smaller surveys). A thorough recalibration of the model will be necessary only when the data with which the model was initially calibrated can no longer validly explain user behavior.

5.15 Because of the data collection requirements (in terms of time, costs, and technical capacity) necessary for modeling, many cities lack the basic databases for conducting a rigorous transport analysis. A common error in Latin America -- resulting from an intention to avoid or reduce the need for data collection -- is the practice of using models that have been calibrated and/or validated in other places. This practice can lead to significant distortions in system analysis, due to the fact that each urban transport system has its own particular characteristics that the models need to reproduce if they are going to be accurate and useful. In reality, no technically adequate alternative exists to replace a reliable, updated database. The first concern of any technically correct analysis must, therefore, be proper data collection.

5.16 Another of the practical barriers to using transport models relates to the scarcity of in-country technical capacity that can competently utilize these models and critically analyze their results. Without a doubt, one of the most important tasks in Latin America, and most of the rest of the developing world, is the creation of this technical capacity. Local technical skill will allow the transport problems in these regions to be confronted from a point of view which is technically consistent with their particular transport characteristics.

VI. CONCLUSIONS

6.1 The use of transport models in Latin America is intimately linked to the need for project evaluation to determine appropriate utilization of scarce resources. The quality of the models is essential to ensuring that investment decisions made based on model results are correct.

6.2 In recent years, theoretical and practical developments in transport analysis have allowed the creation of models that are technically superior to those traditionally used in the field. Simultaneous equilibrium models represent a particular qualitative advance over the classic sequential models. In Latin America, the advent of this new class of models carries significant implications because they allow a more precise and technically reliable study and evaluation of expensive transport projects.

6.3 In addition, the development of more realistic public transport assignment models have represented an important step for transport analysis in Latin America, given the importance of this transport mode in the region. Since, in the long term, probably the only sustainable transport policy for the region will be public transport prioritization, such development of accurate public transport assignment models is critical.

6.4 Despite the advances in transport modeling, certain limitations persist which must be overcome, including more thorough analysis of the land use transport links and of transport's environmental impacts. In both areas significant research and development is occurring, but much work remains to be done before these tools will be technically reliable enough to support policy and investment decisions.

6.5 Among the most important practical limitations to model application in Latin America, it is necessary to mention the difficulties in obtaining adequate data for transport analysis. Although potentially costly to collect, data is indispensable to proper modeling.

6.6 Perhaps the greatest practical challenge, however, comes from the scarcity of technical capacity among planners in the region to both use models and critically analyze their results. Without this capacity, models will simply drive poor or erroneous transport decisions. In the immediate future, the development of a local technical vision will enable local personnel to better address the transport problems particular to Latin American cities and to propose creative and innovative solutions.

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