MOTORIZATION AND URBAN MOBILITY IN DEVELOPING COUNTRIES
EXPLORING POLICY OPTIONS THROUGH DYNAMIC SIMULATION

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Abstract: Degrading condition of urban mobility in developing countries is an important policy issue. The rapid trend of motorization is likely to make the situation further worse. In particular, the declining trend of modal share of public transport in the cities of developing countries manifests a multidimensional problem. Though international patterns and policy experiences offer valuable insights for policy makers, the complex dynamics of urban transport system often resists intuitive policy alternatives. In this paper, a dynamic hypothesis in the form of feedback relationship is proposed and a System Dynamics model is formulated to experiment some of commonly discussed policy alternatives. The simulation result reveals that introduction of off-road rapid transit system is important not only to maintain or regain the modal share of public transport but also to improve road traffic congestion. However, rapid transit system developed too late may bring only limited impact primarily due to unfavorable land-use condition.

Key Words: Urban Transport, Motorization, Developing Countries, Policy Simulation

1. BACKGROUND

Rapid urbanization and growing economic prosperity has brought about a higher rate of motorization in developing countries. However, the level of physical facilities and institutional capacity is not rising adequately enough to manage the pace of motorization. Motorization, urban sprawling, and declining modal share of public transport constitute a vicious cycle and, as a result, mobility and accessibility are declining rapidly particularly in big cities of the developing world (Gakenheimer 1999). Experience in cities of both developed and developing countries demonstrates that public policy can significantly influence resulting pattern of urban transport systems as is visible in the contrasting patterns of private automobile domination in most US cities and public transport led multi-modal system in some European and Japanese cities (Vuchic 1999).

Over the years, important progress has been made in terms of identifying and practically testing various policy measures to improve urban mobility. These measures come in various forms, such as investment for road or rapid transit system, pricing and tax policies, regulatory provisions, public subsidies, and public transport measures. For obvious reasons, the practical feasibility and effectiveness of each of these measures depend upon the specific situation of a country or city. What is also important is to identify the appropriate mix of different measures and timing of their implementation so that they can produce synergistic effects. These measures, when implemented individually or in combination, interact with complex dynamics of urban transport system involving several feedback mechanisms and often produce results that are different from intuitively expected. Further, the static framework utilized in most of
the research studies does not allow examining the dynamic implications of such measures and thereby severely limits the policy relevance of the results.

With the above background, this paper attempts to explore policy options for reconciling the motorization trend with the objectives of achieving sustainable urban mobility in developing countries. A broad review of motorization and urban mobility across the world’s major cities is first presented in the next section. Section 3 identifies the core problem and underlying structure responsible for the problem patterns (in the form of dynamic hypotheses). A simple System Dynamics model is then put forward in Section 4 and the model is utilized for experimenting policy alternatives to be followed by a conclusion.

2. PATTERNS OF MOTORIZATION AND URBAN MOBILITY

Figure 1 shows patterns of per capita travel demand (passenger-km per person per year) using UITP\(^1\) database of major metropolitan areas in the world. In the left panel of the Figure 1, we can see that per capita pass-km increases with income level—just a common sense expectation. However, the correlation is not as strong when the income reaches higher level. This implies that in the early stage of economic development, the increase in the travel demand is largely driven by income growth but in the later stage there must be some other factors at work. And the right panel of the Figure 1, which charts per capita travel demand against urban density, provides an answer for the observed variation in per capita travel demand among high-income metropolitan areas. There is a strong negative correlation between per capita passenger-km and urban density. Metropolitan area with high population density (usually with compact city structure) requires lesser degree of personal travel for a given level of economic prosperity. Per capita travel in some of the North American cities is as high as over 25,000 pass-km per year while the figure for some Japanese cities is even below 10,000 pass-km per capita per year.

![Figure 1. Patterns of City Level Per Capita Travel Demand](image)

Urban mobility measured in terms of pass-km per capita tends to increase in all metropolitan areas of developing countries, as they are likely to experience rapid economic growth. In fact, policy makers have options to make choice between lower or higher level of personal travel by adopting appropriate city structure and urban density. However, regulating city structure strictly is not an easy task. First, the regulatory policy measures to ensure dense urban

\(^1\) Union Internationale des Transports Publics (International Association of Public Transport)
development may not be politically feasible to implement. Next, the mode choice behavior on the part of city residents usually exerts strong structural pressure to negate the effect of regulatory measures. For example, higher car ownership and usage rate encourage urban sprawling thereby increasing level of personal travel. The question of what modal choice individual travelers make to fulfill their mobility need is therefore important to determine the travel demand (per capita pass-km) of city residents.

Figure 2 shows the patterns of car ownership rate (number of cars per thousand population) across major metropolitan areas. The positive correlation between the income level and car ownership rate suggests that the increase in per capita pass-km as a result of income growth is largely supplied by car travel. However, the degree of positive correlation varies widely among metropolitan areas of different countries. European and developed Asian cities are having only moderate level of car ownership even if the income level is high while American cities have high car ownership rate. Though the existing car ownership rate in developing cities is low in absolute measure, for a given income level, it shows a strong similarity with the pattern of US cities. That means if the current trend continues, metropolitan areas in developing countries are likely to follow the mobility pattern of US cities.

Now the question is, can developing countries sustain such a high level of personal travel demand? What will be the quality of urban mobility in developing cities? Even at the current level of travel demand, the situation of urban mobility in developing cities does not look good. Figure 3 (left panel) shows the situation of urban travel speed. The average speed for road network is below 20 km/hour in developing cities. The average speed of bus transport is even worse. In all cities, speed of bus is below the average road speed. And it is interesting to note that the difference is wider when a city gets richer. It is because of the fact that a bus has to share the same road infrastructure with the car traffic. But a car has flexibility in choosing the route while bus does not, and in addition there is delay due to loading and unloading time. So, if the public transport system is based only on bus system, the speed will be always lower.
than that of private mode. However, if public transport is dominated by off-road rapid transit (such as urban railway), average speed of public transport can be higher than that of road network as shown by the cases of Tokyo and Mumbai. Regarding the prospect of improving situation through more road infrastructure, the right panel of Figure 3 does not show encouraging patterns for developing cities, as it appears to be impossible for them to provide road space comparable to that in developed cities.

The above discussed patterns and serious bottleneck of road infrastructure in developing cities suggest an overriding importance of public transport to ensure a sustainable mobility patterns in metropolitan areas of developing countries. Of course, there are other factors too, such as environmental and social justice to justify the importance of public transport. But in this paper public transport’s importance from sustainable mobility perspective has been emphasized. Figure 4 charts the patterns of public transport modal share versus city income per capita across the world’s major cities. And the patterns are not very encouraging for public transport. When city income is low, high percentage of travel demand is served by the public transport but as the income level rises, the modal share of public transport is likely to drop sharply. Individual cases in large metropolitan areas in developing countries follow this trend very closely (Vasconcellos 2001).

3. ISSUES FOR SUSTAINABLE MOBILITY IN DEVELOPING COUNTRIES

In this section, problematic issues related to urban mobility are first discussed and underlying system structure responsible for the observed problem patterns is then suggested in the form of feedback loops diagram (dynamic hypotheses). As the primary focus in this paper is on the strategic policy level, a “macroscopic” perspective has been taken while identifying problems and underlying system structure.

3.1 Key problem issue

Though several problematic issues related to urban mobility can be identified, they are not independent of one another. It is therefore important to identify the core problem, which is observable in the real world, relevant for policy purpose and, most importantly has direct links with other secondary problems. This way the complex set of problem can be reduced to a more tractable form to work on.

Based on the above-discussed patterns and trends, the key issue for sustainable mobility in developing countries can be identified as the pressure from motorization causing a gradual decline in the modal share of public transport. The existing high modal share of public transport in developing cities is primarily a result of captive users. When income reaches higher level and city residents have access to private car, the share of public transport is bound to drop sharply since the service level offered by public transport system primarily
based on conventional bus system is no match to that offered by private car. Such declining trend of modal share of public transport in fact is an empirical manifestation of serious structural problems in the underlying system. Figure 5 presents this problem mode graphically. Now the policy challenge is how to maintain or regain the desirable modal share of public transport. One of the obvious policy options is to develop off-road rapid transit facility, which can offer high service level and thereby compete with private mode. However, as this option requires huge capital investment, there is a tendency among policy makers to postpone such measure till the income level is high enough to afford such investment. However, if the policy measures come too late, the mobility patterns and urban structure may not be in favor of public transport.

3.2 Dynamic Hypotheses

Figure 6 presents a feedback loops diagram to explain the underlying structure responsible for the problem pattern shown in Figure 5. The sign of a link represents the nature of causal relation (positive link means positive causal relation and vice versa). And positive loop polarity means reinforcing loop and negative loop polarity means stabilizing loop (Sterman 2000).

The trend of income growth in developing countries drives the motorization trend causing road congestion, which in turn slows down the motorization. So, as indicated in Figure 6, this loop is a “stabilizing” loop. The congestion on the other hand reduces the attractiveness of on-road public transport, which increases car use (in the absence of rapid transit). Likewise, rapid motorization increases urban sprawling, decreases attractiveness of public transport and eventually increases motorization, thereby setting a strong “reinforcing” cycle. Few other loops can also be identified in the diagram. If this system is left to run on its own (without any policy intervention), the modal share of public transport is bound to drop (as shown in Figure 5) along with other concomitant effects.

The shaded box in the Figure 6 shows different policy measures that can be utilized to direct
the system behavior towards desirable ends. Even though the individual feedback loops seem
to be very simple and intuitive, the simultaneous action of multiple feedback loops is beyond
the intuitive reasoning. The implementation of various policy measures further increases the
complexity of the system.

4. A SYSTEM DYNAMICS MODEL FOR POLICY SIMULATION

As discussed in the above sections, the interaction of motorization and urban mobility in
developing countries constitutes a complex system. The research approaches that treat
narrowly defined problems (often with static perspectives) for the sake of analytical
tractability have serious limitation in producing policy relevant strategic solutions for such
issues. Policy oriented research works in fact have realized the importance of considering
long-term feedback dynamics such as in May (2004). However, the analysis is often restricted
to the graphic presentation of causal loop diagrams, which does not allow running any policy
simulation. The System Dynamics method allows formulating a stock-flow model based on
such feedback structure and then conducting policy experiments. In this section, a brief
introduction of system dynamics method is first presented then a simple System Dynamics
model is formulated based on the dynamic hypotheses presented in Section 3.

4.1 System Dynamics Method

System Dynamics (SD) offers a modeling technique that can capture complex and non-linear
multiple feedback relationships making it possible to consider long-term dynamics of the
system while conducting policy experiments (Forrester 1968). The result of the SD modeling
should not be treated as the statistical forecast; rather its value lies more on long term and
dynamic insights on the direction of system change or required policy. The modeling process
starts with defining the problem mode (Reference Mode in SD lexicon), then identifying
underlying system structure to explain the problematic behavior of the system (in the form of
feedback loops) and specify base model structure in stock-flow system. The base model is
calibrated (based on quantitative or qualitative information) to reproduce the reference mode.
Base model is validated through consistent model structure and realistic simulation behavior.
Finally, policy experiments are conducted over the validated base model. As transport system
involves multiple feedback relationships with high degree of complexities and non-linearity,
SD is an appropriate tool for transport modeling (Abbas and Bell 1994).

4.2 The Model

The model is built around the feedback loops presented in Figure 6. The urban transport
system constitutes private mode, conventional bus services and rapid transit system. As
discussed before, the public transport system in the cities of most developing countries is
relied on the conventional bus, which shares the same road infrastructure with the private
mode leading to eventual decline of modal share of public transport. The base model therefore
assumed only private mode and conventional bus system. The base model is calibrated to
reproduce the reference mode (problem patterns) as presented in the Figure 5. Alternative
policies mainly related to type of urban transport infrastructure including introduction of rapid
transit system (off-road system such as light rail transit, sub-way or suburban heavy rail) are
then tested to assess their effectiveness. The primary emphasis is placed to bring the dynamic
interaction of land-use and urban transport system to the fore.
The model is presented as a recursive system of difference equations (system of stock-flow equations), which is solved using System Dynamics software. The calibration of the model requires assigning values to initial value of stock variables and other parameter values. Initial value of the stock variables is assigned taking the initial state (at the Year zero) of the urban area (an imaginary metropolitan city). The parameter values are assigned to produce a realistic structural relation between the related variables. Rigorous statistical estimation for such multi-equation dynamic model is, in fact, too demanding in terms of data and efforts. As the model behavior is basically driven by the structure rather than the parameter values, SD method allows assigning parameter values intuitively (but based on qualitative and quantitative information) as long as the direction of the slope is not opposite and the value is not outside the realistic range. In this model, assignment of initial stock values and parameter values are guided by descriptive statistics and correlations as obtained from the city-level database compiled by UITP (2001). Some of the parameters are expressed in graphical form as the software can directly read the graphical plots.

The specification of initial conditions of stock variables and exogenous variable depends on the system under consideration. In this paper, a metropolitan area with 3 million populations and per capita city level income of 2000 US$ is assumed (ie at Year 0). The time step used in the model is one year and the modeling time horizon is 50 years. The exogenous population and income growth rate is so chosen as to make the city population 14 million and per capita city GDP 23,000 US$ at the Year 50.

**Urban growth and motorization:** The population and income growth in the metropolitan area drives the overall process of urban growth. In this model both population and income growth rates are supplied exogenously (in the form of graph function).

The population stock accumulation process is formulated as,

\[
POP_t = POP_{t-1} + f_1 POP_{t-1}
\]

Where, \(f_1\) is a graph function for annual metropolitan population growth rate (Figure 7).

Per capita metropolitan income (US$),

\[
IPC_t = IPC_{t-1} + f_2 IPC_{t-1}
\]

Where, \(f_2\) is a graph function for annual growth rate of per capita metropolitan income (Figure 7).

Income ratio,

\[
IR_t = \frac{IPC_0}{IPC_t}
\]

Where, \(IPC_0\) is initial income per capita which is assigned as 2000 US$ per capita.

It is assumed that per capita travel demand is directly proportional to the income level and degree of urban sprawl. The degree of urban sprawl is represented by a ratio of initial urban density (150 persons/hectare) and urban density at a given year. Also, the total travel demand is affected by CR (congestion ratio) and TS (modal share of rapid transit). The idea behind this formulation is that existing level of road congestion adversely affects the gross travel demand. But higher modal share of rapid transit negates such adverse effect, as rapid transit facility is not affected by road congestion. The model determines all of these variables
endogenously (to be presented later).

\[ SR_t = \frac{UD_0}{UD_t} \]  

(4)

The travel demand is computed as stock adjustment process. That is first an expected value is computed which then feeds to the stock.

Expected per capita travel demand (pass-km per person per year),

\[ EPKM_t = \frac{6000SR_t^{0.3}IR_t^{0.3}(1 + TS_t)^{0.3}}{CR_t^{0.3}} \]  

(5)

Travel demand (pass-km per person per year),

\[ PKM_t = PKM_{t-1} + \frac{(EPKM_{t-1} - PKM_{t-1})}{2} \]  

(6)

Stock adjustment coefficient of value 2 is assumed.

Car ownership rate is one of the key variables in this model. As discussed in the previous section, metropolitan income level is the main explanatory variable for the car ownership rate. However, diverse patterns of car ownership rate among countries with similar level of income suggest that there are also other important variables that influence the car ownership rate. Though there might be several policy related factors (such as tax and prices), the most important structural factor is the urban density (represented by the sprawling ratio in this model). Therefore, car ownership rate is expressed as a graphical function of income ratio (IR) and then adjusted by degree of urban sprawl (SR).

Expected car ownership rate (cars/1000 people),

\[ ECW_t = f_3SR_t^{0.3} \]  

(7)

Where, \( f_3 \) is graphical function (Figure 7).

Realized car ownership rate is then obtained through the stock adjustment process, taking adjustment coefficient value as 5 indicating some time delay in adjusting the stock.
Car ownership rate (cars/1000 people),
\[ CW_t = CW_{t-1} + \frac{(ECW_t - CW_{t-1})}{5} \] (8)

Next, important variable is the vehicle-km per car. As in the case of total travel demand, this variable is also assumed to be a function of income level, urban sprawl, road congestion and modal share of rapid transit. All the explanatory variables except the transit share will have similar effect as in the case of total passenger-km per capita. In case of vehicle-km per car, the transit share will have an effect to reduce the distance driven per car. The high share of rapid transit can be taken as a proxy of level of service offered by the rapid transit encouraging car owners to substitute part of car travel with rapid transit use.

Expected vehicle-km by car (vehicle-km per car per year),
\[ EVKMP_{t-CAR} = \frac{6000SR_t^{0.3}IR_t^{0.3}}{CR_t^{0.3}(1 + TS_t)^{0.3}} \] (9)

Realized vehicle-km per car per year,
\[ VKMPC_t = VKMPC_{t-1} + \frac{(EVKMP_{t-CAR} - VKMPC_{t-1})}{2} \] (10)

Per capita travel by car (car pass-km/person/year),
\[ PKMC_t = \frac{CW_t}{1000VKMPC_tCOR_t} \] (11)

Where, car occupancy rate (passenger/car),
\[ COR_t = 2.5 - 0.1IR_t \] (12)

Car occupancy rate varies with the income ratio (IR). For the per capita income of 20,000 US$ (IR=10), COR is 1.5; a reasonable approximation.

As equation (11) gives per capita passenger-km by car, the remaining portion in the per capita total passenger-km (eq 6) is served by public transport. This is reasonable formulation particularly in developing countries where majority of public transport users, especially users of conventional bus services, are captive users. So, the car travel takes its indicated share and the remaining will go to public transport (but rapid transit can compete with private mode as reflected in the formulation of equation 9).

Public transport share,
\[ PTS_t = 1 - \frac{PKMC_t}{PKM_t} \] (13)

Rapid transit development and modal share

As mentioned above, it is assumed that the public transport system is based on the conventional bus and there is no off-road rapid transit system. In this model, rapid transit system is introduced only as a policy alternative. So, the model structure related to the rapid transit system will not be activated during the simulation of base model. When activated for policy simulation, the development of rapid transit system gradually takes the modal share of conventional bus service. Besides, it also causes reduction in car uses shifting it to transit use.
Rapid transit route length (km), \( MTRL_t = MTRL_{t-1} + MTD_{t-1} \) \hspace{1cm} (14)

In the base model, the initial stock value \( MTRL_0 \) of 50 km is assigned at the time of starting rapid transit system. Then onward a rapid transit development rate \( MTD \) of 25 km per year is assumed. However, for the base model both of these values are set zero.

One important question here is how much demand the rapid transit system can command when it is started. The transit demand density is assumed to be a function of urban density \( UD \) and also level of road congestion as road congestion has significant effects on diverting road users (both bus and car) to rapid transit. The demand density also depends on the modal share of the rapid transit as larger share means higher level of services.

Expected transit demand density (pass-km per km track per day) is given by,

\[
ETDD_t = \left[ \frac{7}{9} (UD_t - 15) + 20 \right] CR_t^{0.3} (1 + TS_t)^{0.3} 
\tag{15}
\]

However, the reservoir for rapid transit demand is the total public transport demand. Any possible demand shift effect (from car to rapid transit) is already channeled to the public transport share. So, the maximum demand rapid transit can command is the demand indicated for the public transport (eq 17). However, even for rapid transit system, some minimum level of bus share is necessary as bus service acts as feeder service for the rapid transit. So, it is assumed that the rapid transit at maximum can command 80 percentage of public transport demand. This place the upper limits to the rapid transit demand density.

So, Realized transit demand density (pass-km per km track per day),

\[
TDD_t = \text{MIN} \left[ \left( ETDD_t \right), \left( \frac{0.8 TDPKM_t - TRDPKM_t}{MTRL_t} \right) \right] 
\tag{16}
\]

Where, \( \text{MIN} \) stands for minimum function (which return the minimum of the given values)

Public transport daily demand (passenger-km/day) \( PTDKM_t = PTS_t TDPKM_t \) \hspace{1cm} (17)

Total daily travel demand (passenger-km/day), \( TDPKM_t = \frac{PKM_t POP_t}{365} \) \hspace{1cm} (18)

Rapid transit daily demand (passenger-km/day) \( TRDPKM_t = TDD_t MTRL_t \) \hspace{1cm} (19)

Rapid transit modal share, \( TS_t = \frac{TRDPKM_t}{TDPKM_t} \) \hspace{1cm} (20)

Bus modal share, \( BS_t = PTS_t - TS_t \) \hspace{1cm} (21)

Car modal share, \( CS_t = 1 - PTS_t \) \hspace{1cm} (22)
Road development and road traffic

As mentioned above, the conventional bus service takes the remaining portion of public transport demand after rapid transit takes its share.

Bus daily passenger demand (passenger-km/day),

\[ BDPKM_i = PTDPKM_i - TRDPKM_i \]  

(23)

Assuming bus occupancy rate of 30 passengers per bus and car-equivalent of bus traffic (vehicle-km) as 2,

Car-equivalent of bus traffic (vehicle-km/day) \( CEBVKM_i = \frac{BDPKM_i}{15} \)  

(24)

Total daily road traffic (car-equivalent vehicle-km/day),

\[ TVKM_i = \frac{VKMPC_i}{365} + CEBVKM_i \]  

(25)

In the absence of rapid transit system (base model), road is the only urban transport infrastructure to be shared by private and public mode. It is assumed that at the initial condition (Year 0), the road traffic volume is exactly equal to the road network capacity (the initial value of road stock is assigned accordingly). There is annual increment of road length, which has two parts: an autonomous part, regular annual increment (determined by some decision rule) and policy induced part (additional road development policy).

Road network length (km), \( RL_t = RL_{t-1} + NRD_{t-1} \)  

(26)

The initial road length \( RL_0 \) is 1927 km. The new road development (annual increment) is driven by congestion easing policy (this is part of base model, not policy alternative to be tested). A base increment of 200 km per year is assumed which will be adjusted for congestion ratio (CR). The congestion elasticity of annual road increment for the base model is 100%. That is the base increment for annual road development is increased in the same proportion as the increase in road congestion level.

New road development rate (km/year), \( NRD_t = 200.CR_t \)  

(27)

Assuming that the average daily capacity of urban road network is 3000 car-km/km/day, the Volume-Capacity ratio (termed as congestion ration, CR in this model), is given by,

\[ CR_t = \frac{TVKM_t}{3000.RL_t} \]  

(28)

Urban land development

The population growth along with the urban mobility patterns drives the spatial expansion of the metropolitan area. The newly developed land adds to the size of metropolitan area every year.
Size of metropolitan area (hectare), \( A_t = A_{t-1} + NLD_{t-1} \) \hspace{1cm} (29)

Initial value for the size stock \((A_0)\) is taken as 20,000 hectares.

The demand source for the new land is basically the annual increment of population. But equally important in determining the size of new land development per year is also the required urban density in the newly developed land \((LDD)\).

New land development rate (ha/year), \( NLD_t = \frac{f_t^{POP_t}}{LDD_t} \)

The urban density in the newly developed land, in fact, depends up on the mobility patterns of the metropolitan population. In particular, the modal share of car, bus and rapid transit broadly guide the desirable urban density for the newly developed land. It is assumed that car users prefer low-density development while transit users prefer high-density development. Accordingly, the indicated average urban density for the new land is computed as a function of modal shares.

Average urban density in developed land (person/ha),
\[
LDD_t = (15.CS_t + 30.BS_t)(1 + TS_t)^{0.3} + 200.TS_t \]
\hspace{1cm} (30)

In the presence of rapid transit system, the density preference of car and bus users will also be somehow affected since they will also value the access to rapid transit.

Urban density (person/hectare), \( UD_t = \frac{POP_t}{A_t} \) \hspace{1cm} (31)

Equation (1)-(31) constitutes a recursive system of difference equations. As illustrated in Figure 5, the central element of the problem mode is the declining share of public transport in developing countries’ cities as the income level goes up over the time. One of the hypotheses presented in the previous section for this problem is that only the conventional bus service cannot compete with the private mode and the public transport share is bound to decline given the higher level of car ownership among the city residents. So, to replicate the real world situation in developing countries’ metropolitan areas, the base model (which is supposed to represent the underlying system responsible for the problem patterns) should be simulated without rapid transit system. That is why in the base model the value of rapid transit route length (both initial stock value and annual increment) is set as zero. So, even though, some variables related to rapid transit appear in the model, for the base model simulation these variables will not have any effect (take value of one if it has entered the equation multiplicatively and zero if additively).

Figure 8 shows the time path of key variable when base model is run (variables are plotted on the same chart using multiple scale). Curve-1 is for public transport share (PTS), curve-2 is for congestion ratio (CR) and curve-3 is for road length (km). The base run produced the trend of public transport share as envisaged in the problem mode (Figure 5). Even though congestion responding road development policy as assumed in the base model increases road network length almost by 15 times, the congestion continue to increase. These patterns of
base model simulation closely replicate the real world situation (the time path of other variables not shown here due to space limitation are also in line with the real world trend).

![Figure 8: Base Model Simulation Run](image)

### 4.3 Design of policy experiments

After the base model is validated, the policy experiment is designed. In this model the key policy to be tested is the type of urban transport infrastructure, particularly road transport vis-à-vis off-road rapid transit system. Also tested is the effect of the timing of development of rapid transit system on improving mobility situation in metropolitan areas. Specifically, following policy alternatives are experimented with the base model.

**(a) Aggressive road investment in response to the road traffic congestion (Road Investment):**

This is commonly implemented policy in practice. The most visible problem of urban mobility is the worsening level of congestion in urban roads. As a result, policy option of increasing road infrastructure seems to be intuitively justified and politically appealing. The policy simulation activates this policy by increasing congestion elasticity of new road development in the model equation (27). It should be noted that even in the base model, there is provision of annual road increment. In the base model, a normal annual road development rate (200 km per year) is adjusted with the level of prevailing congestion (multiplying the normal rate by the congestion ratio, CR). This means, for the base model the congestion elasticity of new road development is taken as 100%. Under the aggressive road investment policy, the value for congestion elasticity of new road investment is raised to 300% from the Year 10 until the Year 30 (since the congestion is not severe during first few years). The period of aggressive investment is limited to 20 years as it may not be possible to sustain such policy for longer. Also, the types of road to be developed are of general kinds with no special provisions targeted to improve level of bus services (such as bus priority lane).

**(b) Rapid transit development from Year zero (Early Rapid Transit)**

As the road traffic volume is about to exceed the road capacity in the year zero (initial condition) and car ownership rate is likely to accelerate due to upward trend of income growth, it is reasonable to think, at least strategically, about the importance of rapid transit system (even though the congestion situation is not so serious). So, the prescription under this policy is to develop rapid transit and operate it from the initial year with initial route length of 50 km and average annual increment of 25 km. Given the trend of urban growth, the annual
rate of new rapid transit route development under this policy would continue till the end of model time frame (Year 50).

(c) Rapid transit development from Year 20 (Late Rapid Transit)

As discussed in previous sections, the key bottleneck for developing rapid transit system in developing countries is the lack of financial resources. That is why the notion that “waits until the income level is high enough to finance the investment for rapid transit system” is now getting more and more legitimacy among resource deprived developing countries. So, this policy prescribes that rapid transit development be postponed until sometime later. Under this alternative, rapid transit is started in the Year 20 with same initial stock of 50 km as in the policy alternative (b). But to make it more comparable to the policy (b), the annual rate of route development is doubled to 50 km per year (this is also reasonable from practical viewpoint as the income level would be high enough to provide the investment resources).

4.4 Simulation run and discussion of results

Each of the above three policy alternatives is activated over the base model one by one. That is before activating a policy alternative the model is returned to the base condition. The resulting model behavior in terms of the time path of key variables is illustrated in Figure 9. For the purpose of comparison, Figure 9 also includes the behavior of the base model. The top panel plots the time paths of variable PTS (modal share of public transport), the middle panel plots those of variable CR (congestion ratio) and the bottom panel plots those of RL (Road network length). As indicated in the chart legends, curve-1, is the result of base run simulation same as in Figure 8. Results and implications of simulation run for each policy alternative is discussed below.

(a) Simulation under Road Investment Policy:
Model simulation with Road Investment Policy (aggressive road investment from Year 10 through 30) produced behavior illustrated by Curve-2 in each panel of Figure 9. This policy has no effect on public transport share as the policy is assumed not to have any specific favor to public transport. As expected, there is significant improvement in

![Figure 9. Policy Simulation Results](image-url)
the level of road congestion. Yet, congestion level is still far above the desirable one (value of congestion ratio as less or equal to one). Most notably, as shown in the bottom panel, there is significant increase of road network length (over 40,000 km more than 20 times the initial level).

The result of this simulation implies that the policy of increasing road infrastructure may help reduce congestion to some extent, but it alone cannot get rid of congestion. This is primarily because of the induced road traffic to be generated as a result of improved traffic condition. On the other hand, it would raise a serious question about the total road length required and possible adverse impacts on urban structure due to urban sprawling if such aggressive road investment policy implemented.

(b) Simulation under Early Rapid Transit Policy

Next, the Road Investment Policy is inactivated and Early Rapid Transit Policy is activated. Curve-3 of each panel in Figure 9 shows the time path of corresponding variables when policy of starting rapid transit system from the Year 0 is implemented. The modal share of public transport is significantly improved stabilizing the share at almost 50 percent by the end of the simulation. Surprisingly, the congestion situation under this policy option is as good as that under the road oriented policy (a). Total road length is even less than that in the base run.

Though the improving trend of public transport share under this policy alternative is just common sense expectation, there are some interesting insights the simulation behaviors reveal. Particularly important is the positive effect of rapid transit system on road traffic congestion and required size of the road network. Though in the short-run, the improvement on congestion due to rapid transit is smaller than under policy (a), in the long-run it is almost same but without huge road network. So, this policy serves both objectives; maintaining high share of public transport and relieving the road traffic congestion.

(c) Simulation under Late Rapid Transit Policy

In this simulation run, introduction of rapid transit to the metropolitan transport system is postponed by 20 years; that is it is started at the Year 20 (but with higher annual increments of route length). The simulation behavior is shown by Curve-4 in Figure 9. Even though the annual rate of route extension is doubled than the policy (b), the improvement in public transport modal share is only marginal. Similar is the effect on road congestion too. This simulation shows that effectiveness of rapid transit system in improving urban transport condition is much limited when the system is provided at the later stage. This pattern can be further validated by the case of some US cities where efforts to develop rapid transit system at the much later stage has made very little difference in terms of improving modal share of public transport.

4.5 Replication of real world situation

The simulation results demonstrated that the model replicates, at least in a broad term, the real world situation for problems patterns as well as viable policy solutions. The declining mode share of public transport, which is observable in almost all cities in the world, was replicated in the base model simulation. Likewise, the simulation results of policy run correspond to the practical policy experience of some rail dominated cities (such as Tokyo) in terms of role of urban rail to influence urban land-use and maintain public transport modal share. The model
can be applied for any specific cities by calibrating the model for the given initial condition as most of the structural relationships are valid for a wide range of city condition.

5. CONCLUSION

The patterns of urban mobility across major metropolitan areas in the world suggest that increasing trend of motorization is inevitable in developing countries’ cities. In many metropolitan areas of developing world the problem of road congestion and declining share of public transport is already severe. To explore the possible strategic policy alternatives, this paper first proposed a set of dynamic hypotheses to realistically represent the complex dynamics of urban mobility system and then formulated a System Dynamic model. Road oriented and rapid transit oriented policy alternatives were tested through simulation exercise over the base model in order to assess their impact on the key mobility related variables. The simulation results demonstrated that rapid transit development is important not only for maintaining or regaining modal share of public transport but also improving road traffic congestion. Also, revealed by the simulation is that the impact of delayed investment for rapid transit is very limited. The value of the simulation results perhaps lies more on their direct policy relevance obtained using quantitative techniques with realistic representation of otherwise analytically complex system of urban mobility. The base model also provides a simple but policy relevant experimental platform to understand the complex dynamics of urban transport system. By extending the scope of the model, several other commonly discussed policy alternative can also be tested.

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