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Evaluation of Past Investment in Urban Public Transportation

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Abstract

Mobility is a major concern in cities all over the world. Population and density increase makes urban mobility more complex to plan and budget. Decision makers have to choose which transport projects to build and how much budget to allocate to different types of investments. Cities vary by many characteristics (size, density, etc.), and different cities have adopted different transport solutions. Some cities invested more in road networks while others invested more in public transport (PT) networks. Questions regarding the amount invested in urban public transport and urban roads and the right balance between these investments, taking into account the urban characteristics and the residents' preferences, has received less attention in the literature. In this research, we focused on urban public transport investments in various cities and examine the relationship between public transport and road network investments, speed, GDP, and modal split. The results showed that in developed cities, the current investment in public transport contributes to PT usage and increases PT share. Public transport reserved routes (as an indicator for PT inventory or past investments), jobs proportion in the Central Business District(CBD), and public transport supply were also found to have a positive effect on PT modal split, while motorization level was found to have a negative impact on PT usage as expected. The analysis showed that cities invested on average 7 - 8 thousand US dollars per capita in the public transport infrastructure, accounting for about 50% of the total transport budget. Cities with more developed public transport system invested about 15 thousand US dollars per capita, and allocated 65% of the budget to public transport. These cities manage to maintain the average public transport speed in the range of 30 km/h (on average a 1.3 km/h improvement in the public transport average speed for every 1000 dollar investment per capita). The investments in cities with developed public transport systems generated time benefits that covered on average 0.6 - 0.7 of the investment. Some cities have B/C ratios higher than 1.0, demonstrating that the time benefits predicted by the model covered the investment.

Keywords

City Level Modal Split Model, Urban Public Transport Investment Model, Increase in Public Transport Speed, Public Transport Time Benefits

1. Introduction

Mobility is essential and a major concern in cities all over the world. Increase in population and density makes urban mobility more complex to plan and budget. Limited land and budget resources on the one hand, and growing demand and congestion on the other hand, make city transport planning crucial to enable accessibility, improve productivity and life quality and support activities and economic growth.

Cities vary by size, density, urban structure, population, employment, and socio-economic characteristics. These differences are also reflected in the transport characteristics and the mobility solutions each city has developed. Newman & Kenworthy [1] showed the correlation between urban density and transport energy consumption per capita. They showed that cities with high urban density have lower transport energy consumption.

Commute pattern and modal split also differ significantly among cities. For example, in some US cities (such as Dallas, San Diego, and Columbus) more than 95% of the commuters travel alone by car, while in other cities public transport accounts for about 30% of total commuters (Boston, Chicago, San Francisco and Washington DC). Some cities such as Barcelona, Berlin, Tokyo, Osaka, Prague, Singapore, London, and Paris rely heavily on public transport, which accounts for more than 50% of all motorized trips.

The relationship between transport investments and the economy has been a subject of extensive research in both micro and macro-economic levels. The relationship between transport investment, congestion, road pricing, and transit fare and subsidy is also subject to extensive theory development and research. The micro economic theory of transport investment was developed more than fifty years ago, when the fundamentals of welfare theory as the basis for cost benefit analysis (CBA) were introduced. Berechman [2] described the latest theory and practice evaluation of transport projects. This theory is now in common use in many countries as a practical method for transport project appraisal (see the international comparison by Hayashi, Y. & H. Morisugi [3], Mackie & Worsley [4], and also Vickerman [5] for the United Kingdom, and Shiftan, Sharaby & Solomo [6] for Israel.

New theoretical development has also incorporated macro-economic analysis into the micro-level CBA practice in forms of agglomeration effects and other wider economic impacts [7] [8] [9]. The macro-economics of transport investments usually identify the impact of a transport investment on the gross domestic product (GDP), the labor market and the real estate market. The research in this area is very extensive and shows big variations in the results and magnitude of impact. An extensive review of different approaches and research is described in Banister & Berechman [10] and Berechman [2].

Empirical research of urban public transport investments in cities around the world showed that cities with higher urban density, where more trips are made by public transport, cycling, or by foot, are more efficient in terms of mobility costs [11]. Trip costs in sprawling cities (especially in North America and Oceania where more than 90% of inner city trips are made by car) are 50% more expensive than Western European cities and over 100% more costly than affluent Asian cities. Trip costs to the community are 12.5% of GDP in the USA and Canada, 8.3% in Western Europe, and 5.4% in Asian cities.

Vivier *et al.* [11] showed that on average, public transport consumes four times less energy per passenger km than transport by car (in Canada three times less, in Europe 3.7 times less, and in Japan ten times less.)Sprawling cities in the USA, Canada and Australia have well developed road networks and high motorization levels. Wetern European cities and affluent Asian cities invested more in public transport, hence the ratio of public transport exclusive rights-of-way km to motorway km is more than seven times the average of US and Canadian cities. Asian cities with high density are characterized by developed mobility that is less car dependent and based more on walking, cycling, and publictransport. These cities invested more in public transport with average lenghs that are four times greater than their motorway spans. Wetern European cities are more similar to affluent Asian cities in terms of investment and usage of public transport systems.

Large cities reveal a fundamental difference between private and public transport cost on the supply side. On the one hand, congestion causes increases in the private and public costs of road transportation, while on the other hand, higher population density and investment in public transport infrastructure lowers the cost of using public transport. The cost characteristics of urban transport make urban transport planning difficult and tricky. Investment in city roads increases private car usage and decreases public transport ridership, and thus increases congestion and total generalized costs. This is known as the Down-Thompson Paradox [12]. On the other hand, investment in urban public transport tends to be capital intensive. Berechman [2] showed that inferior transport mega-projects are often selected.

Basso & Jara Diaz [13] developed a combined private car and transit model in which travelers can choose between two modes, car or transit, based on the generalized cost they perceive. The welfare maximization is optimized by three decision parameters: congestion price, transit fare (and hence transit subsidy) and transit frequency representing the investment in transit.

Beaudoin, Farzin, & Lin [14] estimated the effect of past public transit investment on traffic congestion and showed that increases in public transit supply lead to a small overall reduction in auto traffic congestion. The elasticity of auto travel with respect to transit capacity varies from −0.02 for smaller, less densely populated regions with less-developed public transit networks, to −0.4 in the largest, most densely populated regions with extensive public transit networks.

Policy makers, city planners, and researchers each play a role in planning and developing of the city's transport system, choosing which projects should be built, and allocating budget among different types of transport investments such as roads, sidewalks, public transport, and bicycle lanes.

In most countries, an economic appraisal of the projects is made. Planners have to decide how much budget should be invested on transportation, and how this budget should be allocated between public transport projects and roads based on their plans, the availability of funds, potential projects and the benefits of the various projects.

The objective of this research is to analyze past urban public transport investments per capita in various cities and the budget allocation between roads and public transportation. We also aim to study the impact of public transport investments on modal split, speed and accessibility in terms of time savings and benefits.

Chapter 2 describes the research methodology and the city level economic model, and the cities data used in this research. Chapter 3 presents the empirical model results and analysis including the city level modal split model, public transport speed model and the benefits of public transport investments in the cities. Chapter 4 presents the main conclusions of the effects of the investments on public transport speed, modal split and time benefits. The cities included in this research are described in the **Appendix**.

2. Methodology

We developed a cost benefit economic model based on welfare theory as described in Berechman [2]. The difference is that we use some unique approach to the traditional CBA. While CBA is usually used to analyze a specific project, here we calculated time benefits from an investment policy, as set by the actual annual investment made in each city. This approach uses the same theory as the project level cost benefit analysis, but assigns the theory to the network level long term investment. The welfare theory indicates that network investments should produce long term city level benefits. The model described in this chapter aims to capture these benefits.

We used city-level macro data analysis obtained from different sources that are described later in this chapter. We only considered the direct time benefits generated by the transport investment, as the main benefit that estimates (in money terms) the accessibility improvements generated by the project. Time benefits represent a minimum base line of the benefits generated by transport investments. Other benefits such as safety and environmental influences, economic development, and agglomeration are not included in the model and require further research and modeling.

2.1. The Model

We assume a basic aggregate two mode fix demand economic model with city population of Npersons that produces n daily trips which can be described as city commuters who use either public transport or cars.

Figure 1 illustrates the effect of public transport investment in a two-mode model. The equilibrium point E_0 describes equilibrium in the city transport network with n_{pto} public transport commuters and n_{co} car commuters, where $n_{pto} + n_{c0} = n$.

We now assume an annual investment in public transport I that reduces travel costs (such as time) and increases public transport attractiveness and usage. In a two-mode fix demand model, this will imply lower demand for private car trips and a change of modal split into higher usage in public transport (In reality, induced demand of new trips might be attracted to the roads and thus the congestion savings might be less then estimated in the fix demand model, however, this is compensated by not including the benefits of the new trips in the fix demand model).

Point E_1 on Figure 1 describes the new equilibrium after the investment had been made. The public transport supply shifts from S_o to S_1, reduces public transport costs (P_{pt1}) and induces private car users to switch to public transport ($n_{pt1} - n_{pt0}$). The decreased demand for private car trips (D_{1P}) reduces car commuters to n_{c1} and travel costs to P_{c1}.

By the rule of half, the investment in public transport will increase social welfare if total benefits exceed total investment costs as described in Equation (1):

$$I \le \underbrace{\left(P_{pt0} \times n_{pt0} - P_{pt1} \times n_{pt0}\right)}_{\substack{\text{Benefit to existing PT users} \\ \text{(travel time savings)}}} + \underbrace{\frac{1}{2}\left(P_{pt0} - P_{pt1}\right)\left(n_{pt1} - n_{pt0}\right)}_{\text{Benefit to new PT users}} + \underbrace{\left(P_{c0} - P_{c1}\right) \times n_{c1}}_{\text{Benefit to car users}} \quad (1)$$

where,

I = investment in public transport infrastructure,

n = number of trips (city commuters),

With sub index 0 or 1 for before and after the investment respectively,

n_{pt0} = number of travelers by public transport, before the investment,

n_{pt1} = number of travelers by public transport, after the investment,

n_{c1} = number of travelers by car after the investment,

N = city population,

Pc = private car costs (car user's travel time cost),

Tc = car travel time,

Tpt = transittravel time,

Ppt = public transport costs (user's travel time cost).

And we assume in this model that:

$$n_{pt0} + n_{c0} = n_{pt1} + n_{c1} = n$$

As described above, we assume that all costs are time costs, and define:

VOT = value of time,

DTP = daily trips per person.

And so we get:

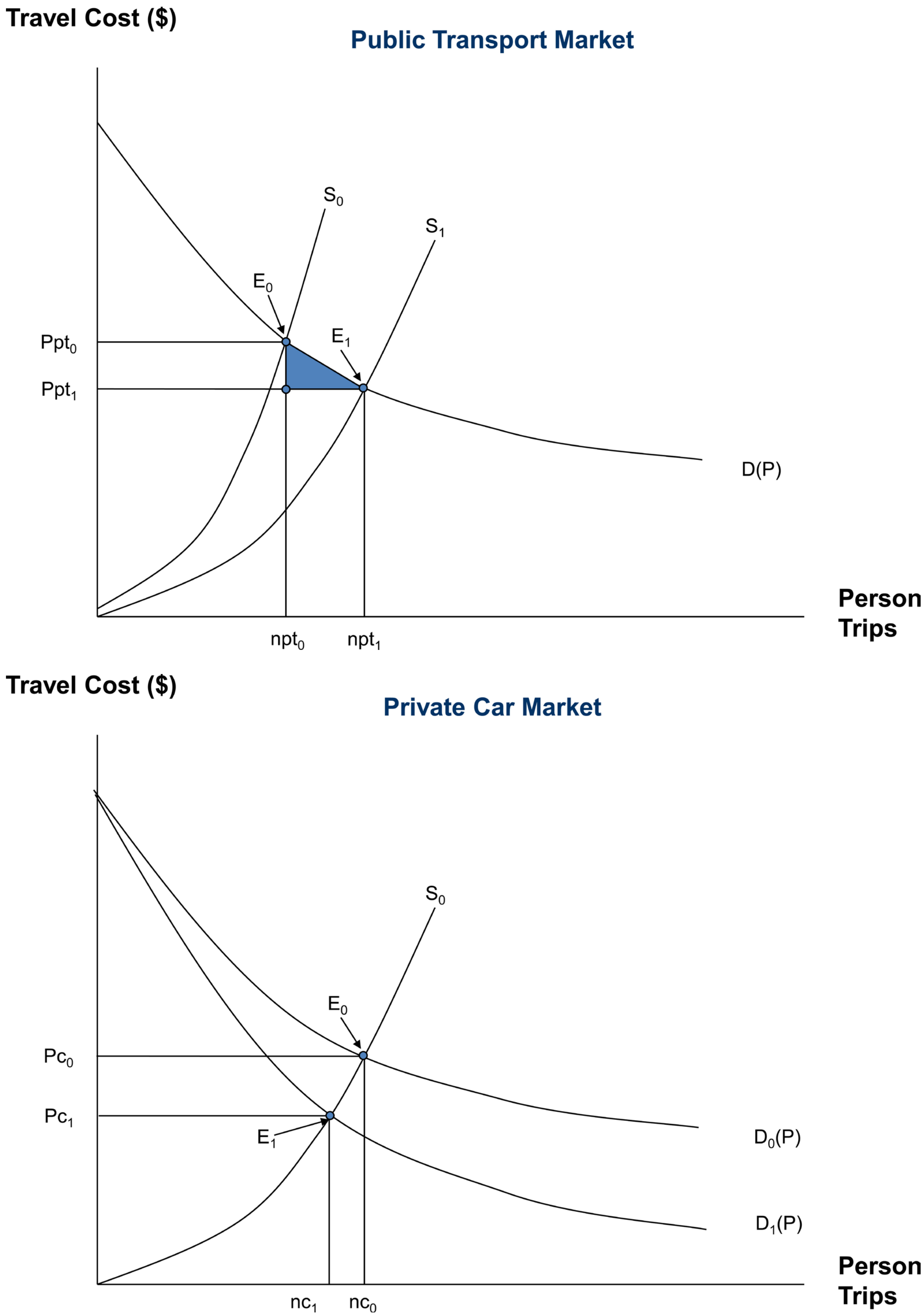

Figure 1. Model illustration: The effect of investment in public transport in a two-mode model. The investment in the public transport network is presented in the figure as a shift of the network supply from S_0 to S_1. This effct is then followed by reduction of car trip demand from D_0 to D_1. The benefits are described in Equation (1).

$$n = N \times DTP$$

Define modal split (share of public transport travelers) as $MS_0 = \frac{n_{pt0}}{n}$ and divide Equation (1) by N and replace:

$$Ppt = Tpt \times VOT$$
$$Pc = Tc \times VOT$$

We get:

$$\frac{I}{N} \le \left[\frac{1}{2}\left(MS_0 \times \Delta T_{pt} + MS_1 \times \Delta T_{pt}\right) + \left(1 - MS_1\right) \times \Delta T_c\right] \times VOT \times DTP \quad (2)$$

Equation (2) is an interesting presentation of the standard Cost Benefit calculation.

On the left side we get the investment per capita, which can now be compared to the result on the right side that shows that the benefits can be represented as:

- The change in travel time in public transport that the investment has caused.
- The change in PT share (increase in public transport trips switching from car trips).
- The change in road network travel time caused by the reduction in car trips and congestion.
- The value of time and average trips per person (per day).

Equation (2) further implies that larger cities should have higher investment per capita in public transport infrastructure.

The model evaluates an entire investment policy as opposed to a single project analysis, but using the project level cost-benefit micro-economic approach to compare the investment per capita in public transport to the time benefits generated. The model is structured as a combined set of sub models describing the current and long term past investments impact on modal split, speed, and travel time. We develop a city-level aggregate modal split based on city characteristics and public transport investments. This is a different approach than the traditional demand elasticity analysis often used in project level analysis.

2.2. Data Sources

We used various data sources and built a combined city-level database. A time series of city-level transport data and modal split data is very limited and often hard to compare. For this research we used these national and city-level data-bases:

UITP Millennium City data base for sustainable mobility—The UITP research database covers 100 cities with more than 200 urban and transport indicators. The research was published in 2001 and includes transport usage by mode, transport supply by mode, energy consumption, financial and cost data, urban network indicators, etc. Although transport data is elaborate, it is limited to a one-year snapshot and does not provide a long-term data series. Table 1 summarizes some main indicators and statistics from the database that were used in this research.

Table 1. Millennium city database main indicators and statistics.

	Average	Min	Max	Std	units
Demographic data					
Number of cities	95				
Population	4,662,123	240,066	32,342,698	32,342,698	persons
Urban density	75	6	230	58	persons/ha
Proportion of jobs in CBD	17	3	75	14	%
Supply indicators					
Length of road per 1000 people	2955	148	9595	2487	m/1000 persons
Parking spaces per 1000 CBD jobs	266	3	1883	294	spaces/1000 jobs
Traffic intensity indicators					
Passenger cars per 1000 people	336	8	746	195	units/1000 persons
Passenger cars per kilometre of road	139	25	696	108	units/km
Private passenger vehicle kilometres per kilometre of road	1,508,890	133,178	4,802,213	948,996	v.km/km
Public transport supply and service					
Total length of reserved public transport routes per 1000 people	100	0	727	127	m/1000 persons
Public transport vehicle kilometres of service per capita	78	15	420	64	v.km/person
Buses per million people	707	77	3154	469	units/10^6 persons
Average speed of public transport	23	11	50	9	km/h
Moibility indicators					
Total daily trips per capita	2.7	1.2	4.7	0.9	trips/person
Percentage of motorised private modes over all trips	51	7	97	23	%
Total public transport boardings per capita	248	11	1036	191	boardings/person
Transport financial cost					
Public transport investment per capita	77	1	407	91	USD/person
Road investment per capita	165	2	847	169	USD/person

EPOMM—European Platform on Mobility Management—We use TEMS, the EPOMM modal split tool, a database of 453 cities (mostly European) with detailed modal split data. The EPOMM member countries complete the best possible data based on as much survey background data as possible. Modal split data of each city is given for a specific year (based on the survey available), mostly from 2006-2013. We use the newer TEMS modal split data where it was available, and complete it with the millennium city database modal split data where it is missing.

See the Appendix for the list of cities with some basic characteristics.

3. Empirical Analysis

In the first step we estimate an aggregate modal split model (MSM) that predicts the percent of public transport trips based on the investment in PT and city characteristics. The MSM model is a regression model estimating the share of public transport trips. The model results are shown in Table 2.

The parameter *PT Invest_developed* is the annual investment in public transport (in US dollars per capita) if the city is in a developed country and zero if the city is in a developing country. The parameter was found positive and significant at the 5% confidence level and shows that investment in public transport contributes to PT usage in the developed world. This parameter was found to be insignificant in the developing world, possibly because of the opposite effects of income increases and investment on modal split.

The *proportion of jobs in the CBD* shows a positive contribution of the strength of the CBD and public transport usage. This parameter is positive but significant only at the 10% confidence level. It was found significant in other variations of the model and given its importance, we decided to keep it in the model.

The past investment in public transport is taken into account by the parameter *total PT reserved routes km per passenger*, the length of all public transport reserved routes such as metro, suburban rail, light rail, and bus rapid transit (BRT) exiting in each city. This parameter was found positive and highly significant showing the contribution of this variable to modal split.

We found a negative contribution of the motorization level to public transport usage. The parameter *passenger cars per* 1000 *people* is negative and highly significant. Finally, the parameter *total public transport annual vehicle km of service per capita* represents the supply of public transport. This parameter reflects the amount of public transport service provided by the city in terms of line length and frequencies, but has some limitations as it does not necessarily show service coverage and effectiveness. The parameter was found to have a positive

Table 2. The City-level Modal Split Model (MSM).

SUMMARY OUTPUT		**Model 1**
		Annual Investmet per capita
Regression Statistics		new modal split data
Multiple R	0.74	**95 cities**
R Square	0.55	
Adjusted R Square	0.52	
Standard Error	14.78	
Observations	95	

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower* 95%	*Upper* 95%
Intercept	42.427	4.689	9.05	2.98784E−14	33.11	51.74
PTInvest_developed	0.037	0.018	2.08	0.040223048	0.00	0.07
Proportion of jobs in CBD	0.181	0.136	1.34	0.185031661	−0.09	0.45
Total PT reserved route km	0.007	0.002	3.87	0.000204436	0.00	0.01
Passenger cars per 1000 people	−0.061	0.009	−7.02	4.2031E−10	−0.08	−0.04
Total public transport vehicle kilometres of service per capita	0.084	0.025	3.33	0.001279612	0.03	0.13

contribution to public transport usage and significance at the 5% level.

Several modal split models were estimated based on the data available. Another version of model 1 (model 1ln) included the logarithmic of the parameter *PT Invest_developed*. This version has yielded very similar results. Many other parameters were tested for inclusion in the model, among them city population, population density, GDP, public transport to car speed ratio, PT speed and mass transit speed. They were found to be less significant in the model when combined with the public transport investment parameter, which is the main parameter we are interested in analyzing.

Since modal split is in the range of 0 - 100, we made sure that the results are not outside the range. We also verified that any reasonable range of the input parameters will result in a model prediction within the 0 - 100 range, thus there is no need for some type of censored model.

The next step of the analysis estimates the PT speed model (PTSM) using regression. The model estimates PT average speed based on the accumulated investment (PT inventory value) in public transport, length of PT reserved routes, and length of roads (**Table 3**). The model is then used to estimate the effect of the additional annual investment in public transport of each city on PT average speed and hence travel time (assuming length of trip remains the same).

The first parameter in the model is the *log of the accumulated investment in public transport*. The two other parameters which were found to be significant are *total public transport reserved route km* and *total length of road per* 1000 *people*.All the parameters have positive contribution to public transport speed. The model shows that higher investment in public transport increases speed logarithmically up to about 30 km/h, as shown in **Figure 2**.

Reserved public transport routes allow PT to travel at higher speed and avoid congestion. This parameter was found to be positive as expected. On the other hand, buses use mainly the road network and are affected by the density and congestion. *The length of road per* 1000 *people* is a measure of the road supply and capacity and was found to have a positive effect on the public transport speed.

In the next step, we estimated a road network (car) speed model (CSM) that relates the network travel speed to traffic density, using regression (**Table 3**). This model is needed to measure the change in car trip time caused by the annual investment in public transport and the shift of trips from car to PT estimated by the modal split model (MSM) in phase 2.

The model uses the parameters: *road density* showing that the reduction in road density will cause travel speed to increase; u*rban density* that was found to have a high negative effect on road network speed, as expected; and *km of freeway in the city* that was chosen to distinguish cities in America and Australia, typified by high-level freeways and higher network speed, from cities in other world regions.

We estimate the accumulated investment in road and in public transport infrastructure (using today's prices). We used current average cost per km of road

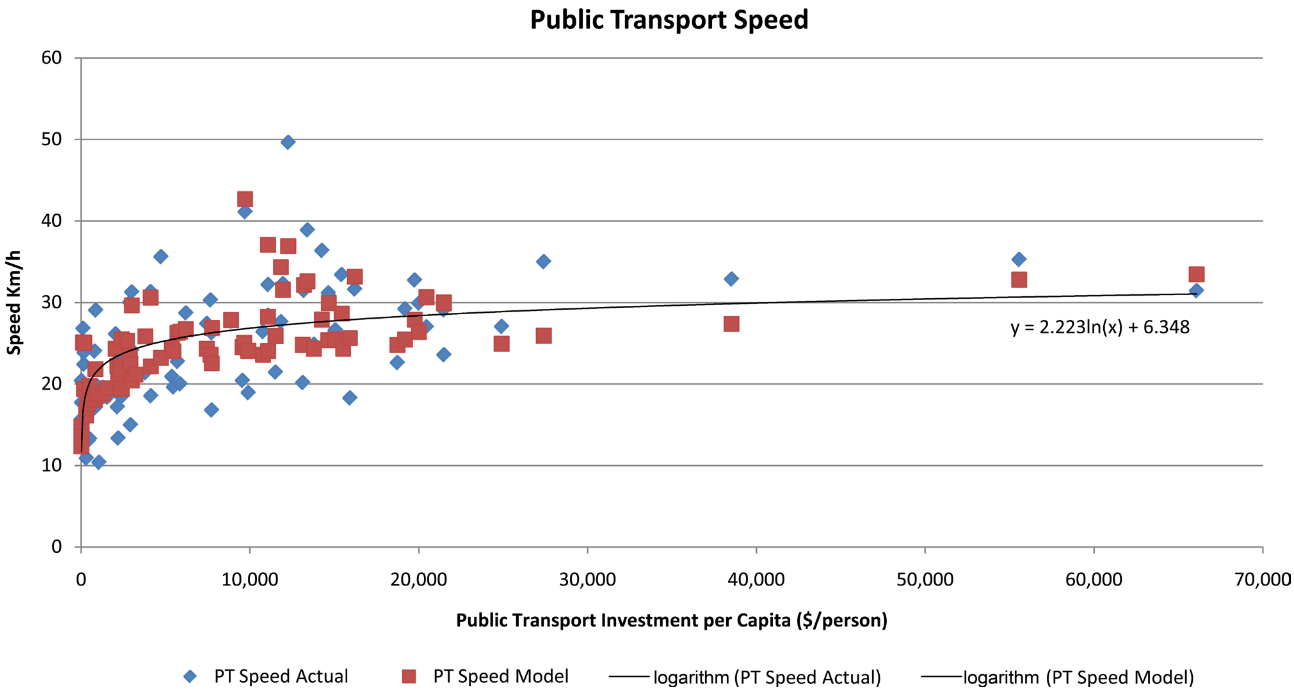

Figure 2. The effect of public transport investment on public transport speed.

Table 3. Public transport speed model and road network (car) speed model.

PT SPEED Model (PTSM)			*Regression Statistics*	
	Coefficients	*t Stat*	Multiple R	0.75
Intercept	**8.8600**	3.46	R Square	0.57
Ln(PTInvest)	**1.2735**	3.89	Adjusted R Square	0.55
Total PT reserved route km	**0.0030**	4.74	Standard Error	4.96
Length of road per 1000 people	**0.0012**	4.89	Observations	83
Car Speed Model (CSM)			*Regression Statistics*	
	Coefficients	*t Stat*	Multiple R	0.68
Intercept	**40.3195**	22.11	R Square	0.46
Road density	**−0.0046**	−1.85	Adjusted R Square	0.44
Urban density	**−0.0689**	−5.50	Standard Error	7.68
Length of freeway	**0.0089**	3.01	Observations	89

and public transport by type of service (urban roads, freeways, metro, suburban rail, light rail, and BRT) to calculate the value of each city transport inventory using today's average construction costs (average cost data is based on Andersson, Gibrand, & Fredriksson [15] and Doll & van Essen [16]). We have also collected data on annual investment in public transport for each city [11].

The last step completes the calculation of the right side of Equation (2):

- Time benefits for existing public transport users based on the change in time estimated by the PT speed model (PTSM).
- Time benefits for private cars users who switch to public transport based on the PTSM model time saving estimates by the rule of half. The number of

new PT users is estimated by the modal split model (MSM).

- Time benefits to car users based on road network speed model (CSM) that estimates travel time savings due to the decrease in road density enabled by the shift to public transport.

We then compared the time benefits on the right side of Equation (2) to the actual annual investment per capita data and calculated the time benefit/cost ratio for each city. This analysis examines the actual annual investment in public transport carried by various cities, and aims to show their long-term benefits in terms of time saving. The model takes into account current public transport and road networks in each city and examines the impact of an additional annual investment policy. It should be noted that the model does not show if the accumulated investment (in terms of public transport inventory) is at this point economically justified, but only the current annual investment policy and its benefits.

The results of the models show (Figure 3, Table 4):

- The results show that the worldwide average investment in public transport per capita (inventory value) was almost eight thousand dollars, accounting for 49% of total average investment in transportation. The table also shows big differences in urban transport investments between world regions. While the total investment in transport in Western Europe and America is similar (in the range of 20 thousand dollars per capita), European cities invested on average 65% in public transport while American cities invested only 24% in public transport.

Table 4 shows the differences of main public transport characteristics for cities with high investments in public transport (more than 10 thousand USD per capita) and cities with low investments in public transport (less than 1500 USD per capita). The analysis shows:

- o The average speed of the public transport network is almost double in cities with high PT investments. In these cities, an investment of 10,000 USD per capita stimulated an increase in the average speed by 13 km/h (an average of 750 USD per capita per 1 km/h increase in public transport speed). Model results show that investment in PT increases public transport share logarithmically up to about 30 km/h.
- o The investment in public transport helped to increase the relative attractiveness of the PT to car use by increasing the PT/car speed ratio from 0.6 to 0.8.
- o Public transport share has remained almost unchanged. The reason for this is that cities with low investment in public transport often have a low GDP and low level of motorization, and accordingly high usage of public transport. This result suggests that developed cities that invested in public transport managed to maintain the modal split even with the growth in the level of motorization.

- The investment in PT generates time benefits that cover on average 0.6 - 0.7 of the annual current investment in public transport.
- Some cities have B/C ratios higher than 1.0, demonstrating that the time

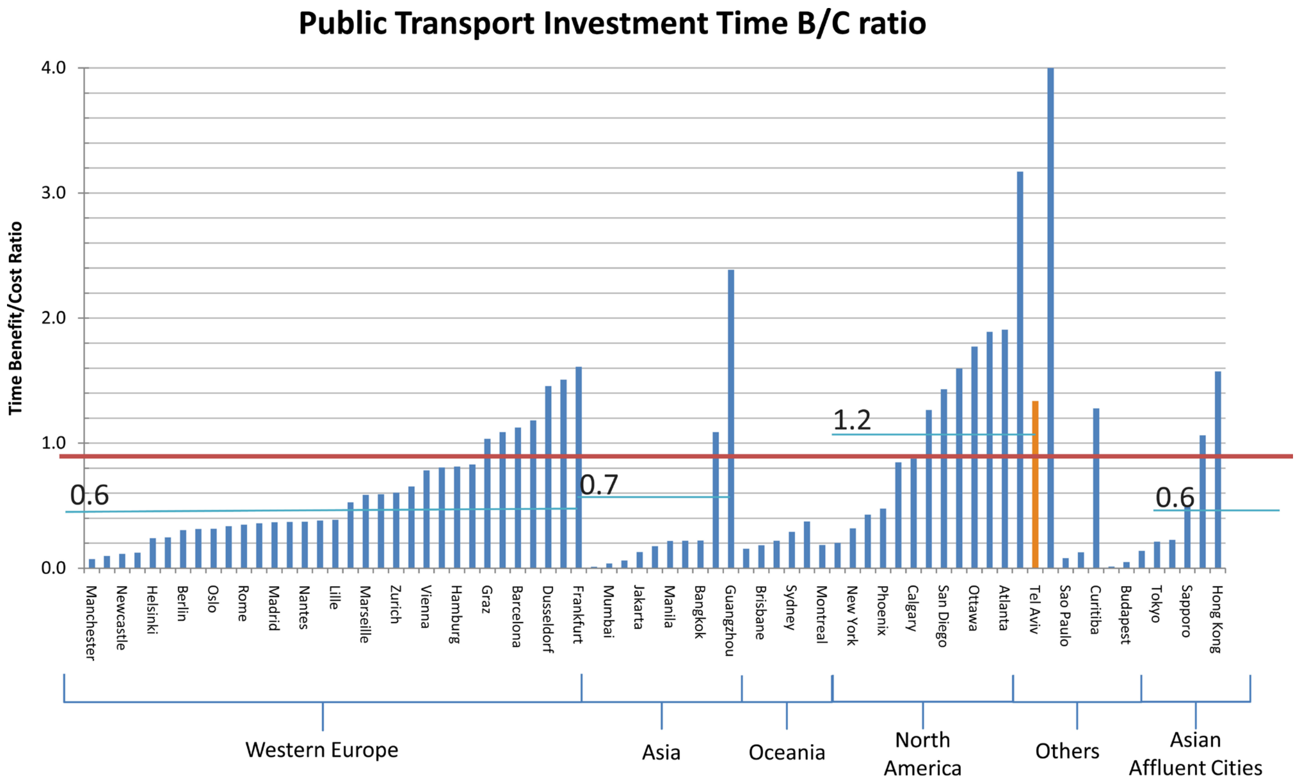

Figure 3. Model results—B/C ratio by world region.

Table 4. Main public transport characteristics for high and low public transport investment cities.

		Low	High
	units	<1500 $/person	>10,000 $/person
No. of Cities	no.	31	25
Average PT Investment	$/person	301	10,133
Average PT Speed	Km/h	17	30
PT/Car Speed	ratio	0.6	0.8
Average PT Share	% PT Trips	38	40
Motorization Level	cars/1000 persons	223	422
GDP	$/person	10,179	31,474

benefits predicted by the model alone cover the investment.

- Cities with developed public transport systems, like Western Europe and affluent Asian cities, invest on average over 200 dollars per person per year. The time benefits generated is on average 0.6 of the investment. The results show that cities with already developed transit systems probably only cover the investment. One of the reasons can be the need for high maintenance and upgrade of existing public transport infrastructure that has a limited contribution to additional time saving.
- Middle East cities have reaped high time benefits for current investment policies. This is probably due to the fact that these cities made almost no pre-

vious investments in public transport, and the improvement gains at the early stages of development can be significant.

4. Summary and Conclusions

In this research, we focused on urban public transport investments in various cities and examine the relationship between public transport and road network investments, speed, GDP, and modal split. We developed a city-level indicative urban public transport investment model based on micro-economic theory to analyze urban public transport investments and the impact on time saving benefits. The model uses city aggregated data and various sub models to estimate the relationship between public transport investments, speed, modal split, and the ensuing time benefits generated by the investment.

The main results of the model:

- In developed cities, PT investment contributed to the use of public transport. Public transport reserved routes (for PT inventory or past investments), jobs proportion in the CBD, and PT supply were also found to have a positive effect on PT modal split, while motorization levels was found to have a negative impact on PT usage as expected.
- A comparison of cities with high and low investments in public transport reveals some interesting characteristics of urban public transport and road investments. The results showed that cities invested on average 7 - 8 thousand US dollars per capita in public transport, accounting for about 50% of the total transport budget. Cities with more developed public transport system invested about 15 thousand US dollars per capita, and allocated 65% of the budget to public transport. These cities manage to maintain the average public transport speed in the range of 30 km/h (on average a 1.3 km/h improvement in the public transport average speed for every 1000 dollar investment per capita.
- The model estimates time benefits for public transport and road network users generated by the investment in public transport. The time benefits for each city are then compared to the investment in public transport. The results show:
  - Investment in public transport increased PT share.
  - The investment in cities with developed public transport systems generated time benefits that covered on average 0.6 - 0.7 of the investment.
  - Some cities have B/C ratios higher than 1.0, demonstrating that the time benefits predicted by the model cover the investment.

There is limited research regarding the investment in urban public transport and road networks and the right balance between these investments. We believe that this research can help to better understand and plan urban public transport networks. The research can contribute to researchers and policy makers to better direct the level of investment and the expected city level impacts.

The model developed in this research has some limitations. The model does not find an optimal investment policy or a general equilibrium between public and private transport. The model analyzes the impact of past public transport investment on time benefits and determines to what extent these benefits cover the investment. The city-level aggregate model is based on city-level average data. This has some limitations to model predication and analysis. For example, congestion and modal split data between the city center and other areas can be very different. Average modal split does not incorporate all the differences between cities' urban structures and characteristics. Average speed changes are limited to over 30 km/h, so the model is limited in its ability to estimate the additional time benefits in cities with already developed and higher speed public transport systems. Some improvements can be introduced to develop the analysis, such as using peak and off-peak data, and adding environmental, safety, and agglomeration benefits.

Further research is needed to investigate the balance between urban public transport and road investments and develop models that will combine more micro and macro approaches. Research focused on a combined model can further analyze the relationship between city size and density and public transport investment, and the effect of the city residents' preferences on the balance between road and PT investment. City-level data was very limited in this research. There is a need for better worldwide annual data on congestion, speed, modal split and travel costs in cities and city centers to understand more about the impact of transport investments.

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Appendix—City Database

City	Country	Region	Population in Metropolitan area Population	Surface area (ha) Surface	Transport modes						
					Bus	Minibus	Tramway	Light rail	Metro	Heavy rail	Other
Abijan	Ivory Coast	AFRICA	2,790,000	56,550	X	X					X
Amsterdam	Netherlands	WESTERN EUROPE	831,499	52,020	X		X	X	X	X	
Athens	Greece	WESTERN EUROPE	3,464,866	253,500	X				X	X	
Atlanta	United States of America	NORTH AMERICA	2,897,178	773,530	X	X			X		
Bangkok	Thailand	OTHER ASIAN CITIES	6,685,000	157,725	X					X	X
Barcelona	Spain	WESTERN EUROPE	2,780,342	33,150	X				X	X	
Beijing	PR China	OTHER ASIAN CITIES	8,164,000	456,790	X	X			X		
Berlin	Germany	WESTERN EUROPE	3,471,418	83,351	X		X		X	X	
Berne	Switzerland	WESTERN EUROPE	295,837	31,358	X		X	X		X	
Bogota	Colombia	LATIN AMERICA	5,569,633	173,000	X	X					
Bologna	Italy	WESTERN EUROPE	448,744	20,300	X						
Brasilia	Brazil	LATIN AMERICA	1,821,946	578,916	X						
Brisbane	Australia	OCEANIA	1,488,883	462,068	X					X	X
Brussels	Belgium	WESTERN EUROPE	948,122	16,051	X		X		X	X	
Budapest	Hungary	EASTERN EUROPE	1,906,798	52,516	X		X	X	X	X	X
Buenos Aires	Argentina	LATIN AMERICA	11,355,562	3,880,000	X			X	X	X	
Cairo	Egypt	AFRICA	13,144,000	143,569	X	X	X			X	X
Calgary	Canada	NORTH AMERICA	767,059	72,173	X	X		X			
Cape Town	South Africa	AFRICA	2,900,000	215,520	X	X				X	
Caracas	Venezuela	LATIN AMERICA	4,550,313	37,000							
Casablanca	Morocco	AFRICA	3,094,000	110,000	X						
Chennai	India	OTHER ASIAN CITIES	6,083,371	116,700	X					X	
Chicago	United States of America	NORTH AMERICA	7,523,328	955,710	X	X			X	X	
Copenhagen	Denmark	WESTERN EUROPE	1,739,458	289,187	X					X	
Cracow	Poland	EASTERN EUROPE	744,987	32,880	X		X			X	
Curitiba	Brazil	LATIN AMERICA	2,431,804	1,330,600	X	X					
Dakar	Senegal	AFRICA	1,939,000	55,000	X	X				X	
Delhi	India	OTHER ASIAN CITIES	11,300,000	148,639							
Denver	United States of America	NORTH AMERICA	1,984,578	949,690	X			X			
Dusseldorf	Germany	WESTERN EUROPE	571,064	20,300	X		X	X		X	
Frankfurt	Germany	WESTERN EUROPE	653,241	24,289	X		X		X	X	
Geneva	Switzerland	WESTERN EUROPE	399,081	24,232	X		X			X	X
Glasgow	United Kingdom	WESTERN EUROPE	2,177,400	480,700	X				X	X	X

Continued

Graz	Austria	WESTERN EUROPE	240,066	12,609	X		X				
Guangzhou	PR China	OTHER ASIAN CITIES	3,853,800	144,360	X						X
Hamburg	Germany	WESTERN EUROPE	1,707,901	69,393	X				X	X	X
Harare	Zimbabwe	AFRICA	1,432,260	58,682	X	X					
Helsinki	Finland	WESTERN EUROPE	891,056	74,300	X		X		X	X	X
Ho Chi Minh City	Viet nam	OTHER ASIAN CITIES	4,811,170	209,370	X	X					
Hong Kong	PR China [HKSAR]	ASIAN AFFLUENT CITIES	6,311,000	109,591	X	X	X	X	X	X	X
Houston	United States of America	NORTH AMERICA	3,918,061	1,737,550	X						
Istanbul	Turkey	EASTERN EUROPE	9,076,865	551,200	X	X	X	X		X	X
Jakarta	Indonesia	OTHER ASIAN CITIES	9,161,000	66,168	X	X				X	
Johannesburg	South Africa	AFRICA	2,448,436	138,400	X	X				X	
Kuala Lumpur	Malaysia	OTHER ASIAN CITIES	3,773,900	285,337	X				X	X	
Lille	France	WESTERN EUROPE	1,153,000	87,900	X			X	X	X	
Lisbon	Portugal	WESTERN EUROPE	2,556,180	312,800							
London	United Kingdom	WESTERN EUROPE	7,007,100	157,900	X			X	X	X	
Los Angeles	United States of America	NORTH AMERICA	9,077,853	1,051,530	X			X	X	X	
Lyon	France	WESTERN EUROPE	1,152,259	48,675	X	X			X	X	
Madrid	Spain	WESTERN EUROPE	5,181,659	802,790	X				X	X	
Manchester	United Kingdom	WESTERN EUROPE	2,578,300	127,200	X			X		X	
Manila	Philippines	OTHER ASIAN CITIES	9,447,156	63,780	X	X		X		X	
Marseille	France	WESTERN EUROPE	798,430	23,850	X		X		X		
Melbourne	Australia	OCEANIA	3,138,147	769,086	X		X			X	
Mexico City	Mexico	LATIN AMERICA	15,748,038	497,400	X	X		X	X		
Milan	Italy	WESTERN EUROPE	2,460,000	62,900	X		X		X	X	
Montreal	Canada	NORTH AMERICA	3,224,130	341,164	X				X	X	
Moscow	Russian Fed	EASTERN EUROPE	8,700,000	109,100	X		X		X	X	
Mumbai	India	OTHER ASIAN CITIES	17,072,000	423,600	X					X	
Munich	Germany	WESTERN EUROPE	1,324,208	30,656	X		X		X	X	
Nantes	France	WESTERN EUROPE	534,000	48,700	X			X			
New York	United States of America	NORTH AMERICA	19,227,361	2,276,340	X			X	X	X	X
Newcastle	United Kingdom	WESTERN EUROPE	1,131,000	54,014	X				X	X	X
Osaka	Japan	ASIAN AFFLUENT CITIES	16,828,737	1,489,100	X			X	X	X	
Oslo	Norway	WESTERN EUROPE	917,852	501,300	X		X		X	X	X
Ottawa	Canada	NORTH AMERICA	972,456	484,000	X						
Paris	France	WESTERN EUROPE	11,004,254	1,201,200	X			X	X	X	
Perth	Australia	OCEANIA	1,244,320	538,686	X					X	X
Phoenix	United States of America	NORTH AMERICA	2,526,113	2,383,850	X	X					

Continued

Prague	Czech Republic	EASTERN EUROPE	1,212,655	48,442	X		X		X	X	
Rio de Janeiro	Brazil	LATIN AMERICA	10,192,097	5,737,800	X		X	X	X	X	X
Riyadh	Saudi Arabia	MIDDLE EAST	3,116,000	146,800	X	X					
Rome	Italy	WESTERN EUROPE	2,654,187	128,530	X		X	X	X	X	
Ruhr	Germany	WESTERN EUROPE	7,356,500	488,759	X		X	X		X	
Salvador	Brazil	LATIN AMERICA	2,663,481	247,780	X					X	
San Diego	United States of America	NORTH AMERICA	2,626,714	1,088,960	X			X		X	
San Francisco	United States of America	NORTH AMERICA	3,837,896	640,600	X		X	X	X	X	X
Santiago	Chile	LATIN AMERICA	5,090,914	226,700	X				X	X	
Sao Paulo	Brazil	LATIN AMERICA	16,562,227	805,100	X				X	X	
Sapporo	Japan	ASIAN AFFLUENT CITIES	1,757,025	112,212	X		X		X	X	
Seoul	South Korea	OTHER ASIAN CITIES	20,576,272	1,174,792	X				X	X	
Shanghai	PR China	OTHER ASIAN CITIES	9,570,000	205,701	X						
Singapore	Singapore Republic	ASIAN AFFLUENT CITIES	2,986,500	64,750	X	X			X		
Stockholm	Sweden	WESTERN EUROPE	1,725,756	649,000	X			X	X	X	X
Stuttgart	Germany	WESTERN EUROPE	585,604	20,462	X		X	X		X	
Sydney	Australia	OCEANIA	3,741,290	1,214,385	X					X	X
Taipei	Taiwan	OTHER ASIAN CITIES	5,960,673	232,437	X					X	
Tehran	Iran	MIDDLE EAST	6,800,000	88,170	X	X					
Tel Aviv	Israel	MIDDLE EAST	2,458,155	151,900	X					X	
Tokyo	Japan	ASIAN AFFLUENT CITIES	32,342,698	1,355,276	X			X	X	X	
Toronto	Canada	NORTH AMERICA	4,628,883	717,491	X		X		X	X	
Tunis	Tunisia	AFRICA	1,874,600	260,000	X			X		X	
Turin	Italy	WESTERN EUROPE	1,451,000	61,200	X		X			X	X
Vancouver	Canada	NORTH AMERICA	1,898,687	282,066	X				X	X	X
Vienna	Austria	WESTERN EUROPE	1,592,596	39,528	X		X	X	X	X	
Warsaw	Poland	EASTERN EUROPE	1,628,500	49,500	X		X		X	X	
Washington	United States of America	NORTH AMERICA	3,739,330	610,580	X				X	X	
Wellington	New Zealand	OCEANIA	366,411	164,100	X					X	X
Zurich	Switzerland	WESTERN EUROPE	785,655	62,582	X		X	X		X	X

Source: Vivier, J., Kenworthy, J., & Laube, F. (2001). *Millenium Cities Database for Sustainable Mobility*. UITP.