OFFICE MEMORANDUM

TO: Mr. E.V.K. Jaycox, through Mr. H. B. Dunker

FROM: G. J. Roth

DATE: December 21, 1978

SUBJECT: The Measurement of Travel Demand and Mobility

1. I attach a copy of Yacov Zahavi's latest paper, which he is presenting this week in Tel Aviv. The paper contains a number of new ideas which may interest departmental staff.

New Definition of "Mobility"

2. In par. 2.2 there is a new definition of "mobility." It is suggested that it be defined as the product of the daily travel distance and daily average speed. While some of us may be unhappy at the use of the old-established word "mobility" to describe a strictly technical concept, it is noteworthy that the concept is similar to that proposed by Harold Dunkerley for our Urban Transport Sector Policy Paper where (on p. 72) he suggested that "it is flow multiplied by speed which most closely indicates the "output" or efficiency of the track." By Dr. Zahavi's definition, "mobility" equals the product of the "output" of the track as described in our Sector Policy Paper, multiplied by the total length of the road or rail network. (The same measure is used for public and private transport.)

Variation of Daily Travel Time with Speed

3. Section 3.1 includes more evidence on the relationship between daily travel time and door-to-door speed. The point of particular interest here is that similar relationships are obtained for Washington, D.C., Nuremberg, and Singapore, all showing that the time spent on travel increases as speed falls. These relationships represent a significant development of the concept of the "stability" of daily travel time per traveler.

A New Method of Forecasting Modal Split

4. Paragraph 3.3 describes a new method to predict "modal split," (i.e. the proportion of travel by different modes) for a two-mode situation, given their speed and cost characteristics, and the time and money constraint of the travelers. Paragraph 3.4 develops the method for forecasting a modal split between three modes, but the solution of this problem requires an assumption to be made about the "utility function" of travel for the population concerned.

Car Ownership Model

5. Paragraph 3.5 describes a new car ownership model; car ownership is derived as part of an iteration process whereby it is made to interact with the demand for transport at the different income levels and the costs of travel by car at different speeds.

Suggestions for "Before and After" Studies

6. Section 4 suggests how travel data collected before and after a
transport change can be compared, as a basis for assessing benefits and costs. The example is illustrated by a comparison of data collected from the Singapore Traffic Restraint Study.

7. All these points are elaborated in the Manual on Urban Travel Patterns which Dr. Zahavi is preparing for the Bank, of which the first draft is expected in January 1979.

cc: Messrs. Churchill, Walters, Stone, Strombom, D.D. Singh, McCulloch (URB); Willoughby, Harral (TRP); Keare, Ingram, Mohan (DED) Hogg (EDI)

GJ Roth: be
THE MEASUREMENT OF TRAVEL DEMAND AND MOBILITY

Yacov Zahavi
Consultant

ABSTRACT

This paper reports on some recent developments in urban transportation models, initiated by the World Bank and currently under further development for the US Department of Transportation and the Ministry of Transportation of the Fed. Rep. of Germany. It is pointed out that simplified versions of complex models usually fail as long as the sophisticated models are not fully satisfactory, and it is suggested that simplified models should be based on new approaches to travel demand analysis, rather than follow in the steps of conventional models. One such example is discussed in the paper, where travel demand is represented by the total daily travel distance per traveler/household, as generated under explicit constraints, instead of travel demand being expressed by trip rates. The paper also suggests a quantified definition of mobility, and shows how the new measures of travel demand and mobility can be applied in the evaluation of changing travel conditions, such as in the Singapore's 1975 Before-and-After studies. The paper concludes with some comments on the technical aspects of data collection to monitor the effects of new transport policies or investments.

Presented at the
Joint International Meeting on
The Integration of Traffic & Transportation Engineering in Urban Areas
Tel Aviv, Israel, December 17-22, 1978
1. SIMPLIFIED MODELS

1.1 In response to the requirements of policy makers, transportation models tended to become increasingly complex during the last decade. Of special concern was the models' lack of accurate responsiveness to such issues as mode choice under new rapid transit systems, road pricing in congested areas, and the effects of gasoline shortage on travel patterns and urban structure.

In the effort to develop sensitive models, each travel component was analyzed thoroughly, and simulated by a detailed model, for example for car ownership, trip generation, trip distribution, modal choice, and trip assignment. Furthermore, each model was further divided into sub-models, such as separate trip generation models for different trip purposes. However, with so many separate sub-models, the interrelationships between travel components received less emphasis, and the complete travel picture tended to be obscured by the oversophistication of the components. For instance, the close interdependence between the daily trip rate and the average trip distance in a city was lost sight of.

It is, therefore, perhaps somewhat paradoxical that concurrent with the development of such complex models to meet users' requirements, there was an increased demand from the same users for simplified models, rapid and easy for application. Indeed, most of the initiative and encouragement for developing simplified models came from such authorities as the Organization for Economic Co-operation and Development (OECD) (1), the National Cooperative Highway Research Program (NCHRP) (2), and the World Bank (2).

(*) This paper incorporates material collected and prepared by the author while working as a consultant to the World Bank, the US Department of Transportation, and the Ministry of Transportation of the Fed. Rep. of Germany. However, the sole responsibility for the views expressed in this paper rests with the author alone.
1.2 The search for new and better transportation models is still going on, and attention has gradually been shifting recently from the development of new techniques to the exploration of new approaches. One such new approach is described in this paper, with special emphasis on the relative simplicity of its application under changing conditions, such as Before-and-After studies.

As the new approach is still under development, and because of the shortage of space, only its general characteristics are described, it being assumed that the reader is familiar with the components and operational phases of conventional transportation models. The new approach was initiated by the Urban Projects Department of the World Bank (3), and is now under development for the US Department of Transportation (4) and the Ministry of Transportation of the Federal Republic of Germany (5).

2. TRAVEL DEMAND AND MOBILITY

2.1 Conventional transportation models, whether aggregate or disaggregate, recursive or simultaneous, are based on four principal phases, namely trip generation, trip distribution, trip modal choice, and trip assignment. The emphasis in these four phases is on 'trips', as trips are assumed to represent travel demand. But do they? On the one hand, it is quite obvious that trips reflect the demand for travel, and a trip will be generated only when the "utility", or benefit, of making the trip to a certain destination for a certain purpose surpasses its "disutility", such as its cost in time and money terms. On the other hand, it appears that trips alone do not suffice to represent travel demand. For example, consider a traveler who is observed to make 6 trips per day in his small home-town, but after moving to a large city is found to make only 3 trips per day; did his travel demand decrease ?; is his utility of travel, and mobility, less in a large city than in a small town ?.

Let us now add another travel component to the above example, namely trip distance, and we find that the trip distance is 5 km. in the
former case, and 10 km. in the latter case. It now becomes evident that the traveler covers 30 km. per day in both cities, within which he trades off trips vs. trip distances. Put another way, city size, which affects trip distances, can also affect trip rates, while the total travel demand, if measured by the daily travel distance, may remain unchanged by city size.

Table 1 presents one such example from England, for the relatively small town of Kingston-upon-Hull and the large metropolitan area of London. Although the size of the study area of Kingston-upon-Hull is only 4.4 percent that of London, the daily travel distance per average car is similar in both cities, while the trip rate and trip distance are inversely related within the total travel distance. The same patterns were also observed in a wide selection of cities in the US, Europe and developing countries (6).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Kingston-upon-Hull</th>
<th>London</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1967</td>
<td>1962</td>
</tr>
<tr>
<td>Population</td>
<td>344,890</td>
<td>8,857,000</td>
</tr>
<tr>
<td>Area, Sq.Km.</td>
<td>107</td>
<td>2,450</td>
</tr>
<tr>
<td>Cars</td>
<td>43,185</td>
<td>1,249,450</td>
</tr>
<tr>
<td>Cars/100 Persons</td>
<td>12.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Car Trips</td>
<td>238,000</td>
<td>4,119,000</td>
</tr>
<tr>
<td>Car Trip Rate</td>
<td>6.25</td>
<td>3.27</td>
</tr>
<tr>
<td>Trip Distance, Km.</td>
<td>4.15</td>
<td>7.18</td>
</tr>
<tr>
<td>Trip Time, Min.</td>
<td>6.9</td>
<td>13.7</td>
</tr>
<tr>
<td>Car Daily Distance, Km.</td>
<td>25.9</td>
<td>23.5</td>
</tr>
<tr>
<td>Car Daily Time, Hrs.</td>
<td>0.72</td>
<td>0.75</td>
</tr>
</tbody>
</table>

An additional interesting result in the above example is that the same inverse relationship also applies to the trip rate vs. trip time within the total daily travel time per average car which, once again, is very similar in both cities, namely 0.72 vs. 0.75 hrs.

One possible interpretation of the above example is that the daily travel demand per average car driver in the two cities, if measured by the total daily travel distance, and for which the traveler has
to pay in both time and money terms, is practically the same. Put another way, if we wish to have a measure of travel demand, that can be generated within certain daily amounts of allocated travel time and money, and which is transferable between cities of different sizes, it appears that the total daily travel distance per representative traveler is a better measure than the daily trip rate.

It is suggested, therefore, that travel demand should be measured by the daily total travel distance, by all modes, per representative traveler. It is shown later in this paper that this measure of travel demand allows us to unify travel demand, system supply, car ownership and urban structure within one operational framework.

2.2 The measure of mobility is currently ambiguous, as it is often used to express a qualitative impression of travel conditions. Mobility is also often used as a synonym for accessibility, as it is evident that the former should be directly related to the latter.

The new definition of travel demand, by travel distance, allows us to define mobility in quantified terms. It is suggested that it be defined as the product of the daily travel distance per representative traveler/household and the traveler's daily average speed.

There are now three independent sources that corroborate this definition. The first is the Alpha-relationship (7), which was derived from empirical analyses of vehicle flows vs. speed on road networks, and can be expressed as:

$$\alpha = qv = Cv^2 ;$$  \(1\)

where:
- \(q\) = flow of vehicles per unit time along a unit length of road;
- \(C\) = concentration of vehicles per unit length of road;
- \(v\) = space-mean speed;
\[ \alpha = \text{a measure specific to a road section, of specific category. For arterials per day, } \]
\[ \alpha \approx 400,000; \text{ for expressways of 4 lanes, } \]
\[ \alpha \approx 2,500,000. \]

The above relationship was also derived from theoretical considerations, and it can be interpreted in terms of the 'kinetic energy' or 'kinetic capacity' that a road section can carry \( (8) \).

Multiplying the Alpha value for a road section by the total length of the road network results in the product of the total vehicle travel distance per unit time (hour or day) and speed.

The second source is a theoretical development of a measure of mobility for a bus system \( (2) \). The requirements of the mobility measure to satisfy certain constraining conditions result in the definition of mobility of a bus system as the product of passenger-kilometers and speed.

The third source is the 'equilibrium assignment', developed upon Wardrop's first principle \( (10) \), which can be stated as: find the assignment of vehicles to road links such that no traveler can reduce his/her travel time from origin to destination by switching to another path. One possible way of solving this problem is by minimizing a convex objective function subject to several explicit constraints \( (11) \). The mathematical solution of this problem is the minimization of the area under the link congestion function, which is expressed by the average travel time per unit distance for a given range of flows. It can then be shown that the above minimization process also equals the maximization of the product of flow and speed. Extending this definition to the total road network expresses the maximization of the product of travel distance and speed.

Thus, three different approaches converge to the same measure of travel productivity, which is defined here as mobility, suggesting that the result is not coincidental. Furthermore, travel distance becomes the common denominator between travel demand and mobility.
The implications of the above results to travel demand modeling are far reaching, as discussed below.

3. TRAVEL DEMAND UNDER CONSTRAINTS

3.1 Most travel choices are made under constraints, such as of time and money. Such constraints are implicit in the mode choice models when dealing with single trips, and they can be extended to be explicit constraints on the total daily travel. For example, the daily time and money spent on travel by representative travelers/households are applied as explicit constraints in various models, such as those based on entropy maximization (12), or utility maximization (13). However, all these models are still based on trips and, furthermore, have to be calibrated to the observed trips in each city. Thus, such models are not fully transferable between cities.

Another approach is to maximize the utility of travel opportunities under the explicit constraints, where the daily travel distance is regarded as a measure of the spatial distribution of opportunities that can be reached within the constraints. This approach is applied in the Unified Mechanism of Travel (UMOT) (2,4,5), in which the conventional phases are reversed; the conventional models start with trip generation and conclude with passenger and vehicle kilometers of travel, while the UMOT process starts with the total daily travel distance that can be generated within the travel constraints, and concludes with trip rates.

Perhaps the best way of explaining the process is by interpreting the relationship of the daily travel distance per representative traveler vs. the door-to-door speed. Figures 1-2-3 show such relationships in two US cities in two periods; the Nuremberg Region in the Fed. Rep. of Germany; and in Singapore respectively. It is to be noted that a traveler in the above cases refers to a person who made at least one motorized trip during the survey day.
In the first two cases travel is by motorized modes only, while in Singapore the data also include walking trips by motorized travelers. Furthermore, the data of Nuremberg also include regional travel.

![Graph showing travel distance vs. door-to-door speed](image1)

**Figure 1**: Daily Motorized Travel Distance per Traveler, by Mode, vs. Door-to-Door Speed, Washington, D.C. 1955 + 1968 and Twin Cities 1958 + 1970

![Graph showing daily travel distance vs. door-to-door speed](image2)

**Figure 2**: Daily Travel Distance per Traveler, by household class, vs. Door-to-Door speed, Nuremberg Region 1975
The above relationships are summarized in Table 2. From these relationships we can also derive the relationships between the daily travel time per representative traveler vs. the door-to-door speed, as shown in Figure 4 for the three cases.

Table 2: Travel Characteristics of Travelers vs. Door-to-Door Speed, Based on the Function: Travel Distance = a + b(speed), km.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Washington, D.C. + Twin Cities</th>
<th>Nuremberg</th>
<th>Singapore</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Observations</td>
<td>172</td>
<td>55</td>
<td>28</td>
</tr>
<tr>
<td>a</td>
<td>2.18</td>
<td>1.76</td>
<td>2.01</td>
</tr>
<tr>
<td>b</td>
<td>1.03</td>
<td>1.20</td>
<td>1.10</td>
</tr>
<tr>
<td>R²</td>
<td>0.87</td>
<td>0.92</td>
<td>0.86</td>
</tr>
<tr>
<td>Maximum Time at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking Speed, hr.</td>
<td>1.50</td>
<td>1.58</td>
<td>1.53</td>
</tr>
<tr>
<td>Distance/TR at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking Speed, km.</td>
<td>7.0</td>
<td>7.4</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Figure 4: Daily Travel Time per Traveler, Washington, D.C. + Twin Cities, the Nuremberg Region and Singapore
The results can be interpreted in the following way:

(a) When speeds increase, travelers are observed to both travel further and save real time; part of the saved time is traded off for more travel distance (induced travel), and part is saved in real time terms;

(b) The saving in the daily travel time is especially significant when low speeds increase, such as when travelers transfer from bus to car. This trend may account for the reluctance of car travelers to transfer back to bus; they then have to spend more time in order to travel less distance;

(c) At relatively high speeds, the daily travel time is relatively stable, most of the saved time being traded off for more travel distance;

(d) When extrapolating the relationships to the speed of walking, about 4.7 kph (14), all converge to about 1.5 hours per representative traveler per day. Thus, the range of the daily travel time is relatively narrow, from a maximum of about 1.5 hrs. to a minimum of about 1.0 hrs.

It should be noted that the above relationships represent favorable travel conditions, where the travelers have the freedom to adjust their travel within their constraints. However, under unfavorable travel conditions, such as observed in some cities of developing countries, where the poor reside at the fringe of the urban area, and have to travel far to job locations, the minimum travel distance can become the binding constraint, and the travelers under such conditions may have to spend as much time and money as required in order to reach jobs. Hence, the distributions of the daily travel time per traveler, by income and location, strongly influence urban travel patterns.

Another point to note is that the coefficient of variation (standard deviation over mean) of travel times and distances are very similar for all groups of representative travelers when stratified by such factors as income and location.
3.2 The second principal constraint on travel is the money constraint. The available data from the US suggests that a representative household is willing to spend on travel a maximum of about 11 percent of income (or slightly more if compared to the disposable income)\(^{(15)}\).

About the same proportions were also noted in Canada and England. Furthermore, the above proportion is stable for households owning cars at all income levels. Households not owning a car, on the other hand, spend less than 11 percent of their income on travel, and one possible explanation for this trend is that the travelers of such households spend their daily travel time budget much before they reach even 6 percent of their income.

3.3 Travel demand, by distance, can now be derived within the two constraints. Following is a simple example, where there are only two modes, bus and car, and two constraints \(^{(*)}\).

If we define:

\[
\begin{align*}
x_1, x_2 &= \text{daily travel distance by car and bus respectively;} \\
t_1, t_2 &= \text{time per kilometer of car and bus respectively;} \\
c_1, c_2 &= \text{cost per kilometer of car and bus respectively;} \\
T &= \text{daily travel time budget per household;} \\
M &= \text{daily travel money budget per household;} \\
\end{align*}
\]

then:

\[
\begin{align*}
x_1 t_1 + x_2 t_2 &= T \\
x_1 c_1 + x_2 c_2 &= M \\
\end{align*}
\]

Thus, solving the two equations with the two unknowns results in the following outputs: (i) total daily travel distance per household, \(x_1 + x_2\); (ii) modal split by distance, \(x_1\) vs. \(x_2\); (iii) time and money allocated to each mode, \(x_1 t_1; x_2 t_2; x_1 c_1; x_2 c_2\); (iv) average speed, \((x_1 + x_2)/T\); and (v) the measure of mobility, as the product of \((x_1 + x_2)\) and average speed.

\(^{(*)}\) When the number of modes equals the number of constraints, there is no need to maximize an objective function, as the problem can be stated uniquely in terms of 'n' equations with 'n' modes.
By this method, travel demand by distance, modal choice and mobility, are all direct outputs from one process.

Table 3 summarizes the time and money budgets and unit costs of travel for representative households, by income, in Washington, D.C. 1968, and the resulting demand for car and bus travel distance. The estimated values are shown in Figure 5 as continuous lines vs. the observed values, where a close similarity is observed. In contrast, conventional trip generation models have to be calibrated to the observed trips and, hence, their ability to reproduce the same observed trips does not ensure their validity, especially for forecasts. The ability of a model based on constraints to reproduce observed travel characteristics independently, provides a better assurance for its validity.

<table>
<thead>
<tr>
<th>Annual Income, $</th>
<th>4,000</th>
<th>5,000</th>
<th>6,000</th>
<th>7,000</th>
<th>8,000</th>
<th>9,000</th>
<th>10,000</th>
<th>11,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars/8H</td>
<td>-</td>
<td>(0.1)</td>
<td>0.35</td>
<td>0.71</td>
<td>1.02</td>
<td>1.29</td>
<td>1.54</td>
<td>1.76</td>
</tr>
<tr>
<td>TN-budget, $</td>
<td>0.51</td>
<td>0.75</td>
<td>1.26</td>
<td>2.01</td>
<td>2.82</td>
<td>3.17</td>
<td>3.53</td>
<td>3.88</td>
</tr>
<tr>
<td>TT-budget, hr.</td>
<td>2.02</td>
<td>2.02</td>
<td>2.09</td>
<td>2.20</td>
<td>2.29</td>
<td>2.41</td>
<td>2.53</td>
<td>2.63</td>
</tr>
<tr>
<td>CAR: v, kph.</td>
<td>13.5</td>
<td>15.0</td>
<td>16.0</td>
<td>19.0</td>
<td>21.0</td>
<td>24.0</td>
<td>26.0</td>
<td>28.0</td>
</tr>
<tr>
<td>c, $/km.</td>
<td>0.104</td>
<td>0.096</td>
<td>0.092</td>
<td>0.081</td>
<td>0.075</td>
<td>0.068</td>
<td>0.064</td>
<td>0.060</td>
</tr>
<tr>
<td>D, km.</td>
<td>0.02</td>
<td>2.39</td>
<td>8.40</td>
<td>19.74</td>
<td>34.14</td>
<td>42.38</td>
<td>50.81</td>
<td>60.59</td>
</tr>
<tr>
<td>TRANSIT: v, kph.</td>
<td>6.8</td>
<td>7.5</td>
<td>8.0</td>
<td>9.5</td>
<td>10.5</td>
<td>12.0</td>
<td>13.0</td>
<td>14.0</td>
</tr>
<tr>
<td>c, $/km.</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
<td>0.037</td>
</tr>
<tr>
<td>D, km.</td>
<td>13.63</td>
<td>13.96</td>
<td>12.52</td>
<td>11.02</td>
<td>6.97</td>
<td>7.73</td>
<td>7.45</td>
<td>6.56</td>
</tr>
<tr>
<td>Total Distance</td>
<td>13.65</td>
<td>16.35</td>
<td>20.92</td>
<td>30.76</td>
<td>41.11</td>
<td>50.11</td>
<td>58.26</td>
<td>67.15</td>
</tr>
</tbody>
</table>

Figure 5: Estimated vs. Observed Daily Travel Distance per Household, by Mode, vs. Income by District, Washington, D.C. 1968.
3.4 Figure 6 shows the results of an exercise, based on Table 4, for three modes—walking, bus, and private modes—and two constraints.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Walking</th>
<th>Transit</th>
<th>Private Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door-to-Door Speed, kph.</td>
<td>4.30</td>
<td>8.60</td>
<td>17.20</td>
</tr>
<tr>
<td>Time per Kilometer, min.</td>
<td>13.95</td>
<td>6.98</td>
<td>3.49</td>
</tr>
<tr>
<td>Cost per Kilometer, $</td>
<td>0.01</td>
<td>0.03</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The results are of special importance, as they suggest that:

(a) There is an income threshold, below which a representative traveler cannot afford even a bus fare on a regular basis, as is the case in cities of some developing countries; after this first threshold is crossed, the traveler starts to use bus travel. After a second income threshold is crossed, the traveler starts to use private modes, such as motorcycles and cars;

(b) While walking and travel by private modes are monotonic, decreasing and increasing consistently with income, travel by bus reaches a maximum value at a certain income level, after which it declines. This trend, although known from actual experience
in all cities, is now explained by the UMOT process. The analysis also suggests that the key to a better public transport system, that will attract passengers from the private modes, is high speed, rather than low fares.

3.5 The last subject in this section is car ownership. Conventional transportation models assume that car ownership is a principal factor in trip generation and, hence, the outputs from a car ownership model are introduced as inputs into the trip generation model. In the UMOT process, travel demand, car ownership and transportation system supply interact by a feedback process according to the following steps (4):

(a) The travel demand process results in the demand for car travel-distance, as one of the outputs;

(b) The demand for car travel-distance generates car ownership, in order to satisfy the demand;

(c) The interactions between the estimated number of cars and a given road network results in unit costs of travel, in time and money terms;

(d) The new unit costs are then fed back into the travel demand phase, and the sequence is repeated until, by a process of iteration, the total transportation system approaches equilibrium between demand and supply.

It should be noted at this stage that travel demand in the conventional models is expressed by trips, while the outputs of system supply is expressed by the passenger and vehicle kilometers of travel at certain speeds. Hence, demand and supply in such models have no common denominator. In the UMOT process, on the other hand, the travel distance is a common denominator in both the demand for, and the supply of, travel, and the iteration process described above searches the equilibrium point between the two. The travel system is then found to converge rapidly.
Figure 7 shows an example of the car ownership estimation process, based on the demand for car travel-distance, as detailed in Table 3; the distributions of travel distance about the mean distances (coefficient of variation is 0.5); minimum daily travel distance that would justify the purchase of cars (14 and 55 pass.km. for 1 and 2+ cars per household); and the probability of a household at a given income level to own a car versus the observed levels are summarized in Table 5, where a close similarity between the two is observed.

Figure 7: Probability of Car Ownership per Household vs. Income, by District, Washington, D.C. 1968
Table 5:
Car Ownership (based on a Normal Distribution), by District, Washington 1968

<table>
<thead>
<tr>
<th>Annual Income, $</th>
<th>6,000</th>
<th>7,000</th>
<th>8,000</th>
<th>9,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Pass.Km. (μ)</td>
<td>8.40</td>
<td>19.74</td>
<td>34.10</td>
<td>42.38</td>
<td>50.81</td>
</tr>
<tr>
<td>S.D. (σ) = 0.50</td>
<td>4.20</td>
<td>9.87</td>
<td>17.07</td>
<td>21.19</td>
<td>25.41</td>
</tr>
<tr>
<td>Prob. 1 car (1)</td>
<td>0.10</td>
<td>0.72</td>
<td>0.881</td>
<td>0.910</td>
<td>0.926</td>
</tr>
<tr>
<td>Prob. 0 Car</td>
<td>0.50</td>
<td>0.28</td>
<td>0.119</td>
<td>0.090</td>
<td>0.074</td>
</tr>
<tr>
<td>Prob. 2 cars (2)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.111</td>
<td>0.275</td>
<td>0.434</td>
</tr>
<tr>
<td>Prob. 1 car only</td>
<td>0.10</td>
<td>0.72</td>
<td>0.770</td>
<td>0.535</td>
<td>0.492</td>
</tr>
<tr>
<td>Avg. Car Ownership (3)</td>
<td>0.10</td>
<td>0.72</td>
<td>1.014</td>
<td>1.240</td>
<td>1.447</td>
</tr>
<tr>
<td>Observed Car Ownership</td>
<td>0.35</td>
<td>0.71</td>
<td>1.02</td>
<td>1.29</td>
<td>1.54</td>
</tr>
</tbody>
</table>

(1) Assuming 14 pass.km. as the minimum threshold for 1 car;
(2) Assuming 55 pass.km. as the minimum threshold for 2 cars;
(3) Avg. car ownership = (Prob. 1 car) + 2.2(Prob. 2 cars).

In conclusion to this section, a new approach to travel demand is presented, that allows us to analyze travel conditions, and evaluate alternative policy options, in a rapid and consistent way. The implications of this approach for travel conditions in an actual case are discussed in the following sections.

4. BEFORE-AND-AFTER STUDIES

4.1 The following is a short presentation of part of the travel data collected before and after the introduction of the Area License Scheme (ALS) in Singapore's central business district in June 1975, which imposed a fee on each car and taxi with less than 4 persons that entered the restricted zone during the morning peak period. The presentation is general and macro in scope, referring to part of the travel data collected from a sample of about 2,000 vehicle and non-vehicle owning households, that were interviewed both before and after the introduction of the ALS. Full details about the surveys can be found in the World Bank Staff Working Paper No. 281 (16).

The principal difference between the Bank's Paper and this section is that the former presentation concentrated mainly on selected trips, that were either destined to the restricted zone or directly affected by the ALS, while the following presentation is based on the total travel in the Singapore area.
As the original data do not include sample expansion factors, more emphasis is put on the following relationships, by income, than on the total averages. Furthermore, when comparing the "Before" and "After" data, the following points should be noted:

(a) The AIS was introduced during an economic slow-down and, therefore, the differences found cannot be specifically attributed to the AIS. For instance, it is noted in the World Bank's Paper that shopping trips by members of vehicle-owning households to destinations in the restricted zone fell by 25 percent, compared with a decline by 14 percent to destinations outside the zone. But even the difference in the percentages, such as 25 - 14 = 11 percent, cannot be attributed to the AIS alone, as a general decentralization process was active in Singapore during the AIS period. Altogether, therefore, the World Bank's Paper is careful in noting that the specific effects of the AIS could not be isolated explicitly;

(b) While the flows of cars entering the restricted zone fell dramatically, by about 70 percent, during the morning peak-period, when the restrictions were imposed, no significant change was noted in the traffic flows of cars leaving the restricted zone (including through traffic) in the afternoon period. Hence, while the AIS restrictions had a direct and impressive effect on traffic flows during the morning hours, its total daily effects could not be identified and quantified; as if car travelers only shifted their time of travel, but not changed their mode. For example, out of about 10,000 parking spaces prepared around the restricted area, with the hope that car drivers would transfer to a bus shuttle-service to the restricted zone, only about 300 spaces were in fact used. Put another way, car drivers appear to have adjusted their travel patterns in ways other than anticipated;

(c) The results of the sampled home interview Before-and-After studies could not be fully verified because of the lack of recorded data on (i) traffic speeds and (ii) bus passenger loadings.
Despite these weaknesses, the results, based on the "Before" and "After" two home-interview surveys only, can be illuminating, as they reveal several intrinsic characteristics of travel behavior.

4.2 Because of space shortage, only several selected relationships are shown, stratified by income alone. Therefore, part of the variability in the trends may result from such factors as household size and household location, as well as from sampling errors. The trends are per average traveler, and the travel time is the reported door-to-door time. The comparisons are divided into households owning and not owning a private vehicle, and "Before" and "After" the introduction of the AIS.

Figure 3: already showed the relationship between the daily travel distance per traveler of vehicle and non-vehicle households vs. the door-to-door speed. The "Before" and "After" points intermingle, suggesting that the basic travel behavior remained unchanged;

Figure 8: shows the daily trip rate per traveler. The daily trip rate per traveler is very low, barely over the minimum of two trips. Of special concern is the result that the trip rate per traveler of vehicle-owning households is similar to the trip rate per traveler of non-vehicle households. It is not clear at this stage whether these low trip rates are due to underreporting of trips, or are a characteristic of the travel in Singapore, but the high trip rate per average car, about 5 trips per day, as derived from a comprehensive study, may suggest that the former possibility is more probable.

The daily trip rates of all travelers appear to have decreased during the AIS period, especially for travelers of high income households. As a general comment, if such trends are found in a survey, it would be advisable to recheck the original data carefully in order to identify their causes.
Figure 8: Daily Trip Rate per Traveler vs. Household Income
Singapore Before-and-After Study

Figure 9: shows the daily travel distance, by car and public transport, per traveler of vehicle-owning households (*). The first striking result is that the general trends of the relationships follow those of the exercise shown in Figure 6, namely that while car travel increases monotonically with income, transit travel reaches a peak, after which it declines. While no data on travel costs in money terms, nor the number of travelers per household, are detailed in the available tabulations, the travel patterns suggest that travel distance is affected by both speed and income, as discussed above.

Figure 9: Travel Characteristics of Travelers belonging to Vehicle-Owning Households, Singapore Before-and-After Study

(*) The data also include the daily travel distance by motorcycles, bicycles and walking, but these distances are relatively short.
The second striking result is that the daily travel distance by car declined at all income levels, while only a slight shift to bus travel is noted. While this trend cannot be attributed solely to the AIS, the shift is significant and consistent. However, whereas the loss for car travel is great, the gain for transit travel is small, corroborating the indication that modal shifts should take into account the gain or loss of travel and mobility within the daily constraints. This basic phenomenon can be seen in Table 6, where the above data for travelers of vehicle-owning households are compared.

Table 6: Daily Travel Distance, by Car and Transit, per Average Traveler of Car-Owning Households, Singapore Before-and-After Study

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
<th>Change, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Distance, km.</td>
<td>7.75</td>
<td>6.70</td>
<td>-13.6</td>
</tr>
<tr>
<td>Transit Distance, km.</td>
<td>6.71</td>
<td>7.04</td>
<td>+4.9</td>
</tr>
<tr>
<td>Car + Transit, km.</td>
<td>14.46</td>
<td>13.74</td>
<td>-5.0</td>
</tr>
<tr>
<td>Total, all modes, km.</td>
<td>16.26</td>
<td>15.27</td>
<td>-3.2</td>
</tr>
<tr>
<td>Speed, kph.</td>
<td>12.84</td>
<td>12.23</td>
<td>-4.8</td>
</tr>
<tr>
<td>Total Mobility</td>
<td>209</td>
<td>187</td>
<td>-10.5</td>
</tr>
</tbody>
</table>

It appears that the loss of travel distance by transfer from car to public transport is 5 percent, and the total loss, by all modes, is 3 percent. It is also indicated that the transfer from car to transit by travelers of vehicle-owning households cannot be attributed to the AIS, as the daily travel distance by public transport per traveler of non-vehicle households decreased as well, by about 5 percent. Hence, the most plausible cause for the above results, affecting both vehicle and non-vehicle households alike, appears to be the general economic slowdown during the AIS period.

Figure 10: shows the mobility of travelers of vehicle and non-vehicle households, and Table 7 summarizes the relevant data. (The data in this case include travel by all modes). While no major change is noted for non-vehicle households,
the mobility of vehicle-owning households dropped significantly.

One of the main advantages claimed by the proponents of road pricing is that it allows travelers at all income levels to increase their mobility. However, as the mobility of vehicle-owning households actually decreased consistently at all income levels, it may be inferred that this gain was not realized in practice. This may have been due to the level of the AIS fee, which has resulted in the streets within the zone to be underutilized during the hours of restraint. Non-vehicle households, on the other hand, were not affected much by the AIS fee, thus corroborating the indication that non-vehicle households are affected more by speed than by travel costs, especially at medium and high levels of income.

![Graph showing mobility per traveler of vehicle and non-vehicle owning households, Singapore before-and-after study](image)

**Figure 10:** Mobility per Traveler of Vehicle and Non-Vehicle Owning Households, Singapore Before-and-After Study

<table>
<thead>
<tr>
<th>Household Monthly Income S$</th>
<th>Owning Vehicle</th>
<th>Non Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>0 - 200</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>200 - 400</td>
<td>124</td>
<td>83</td>
</tr>
<tr>
<td>400 - 700</td>
<td>152</td>
<td>127</td>
</tr>
<tr>
<td>700 - 1,000</td>
<td>168</td>
<td>140</td>
</tr>
<tr>
<td>1,000 - 1,500</td>
<td>203</td>
<td>195</td>
</tr>
<tr>
<td>1,500 - 2,000</td>
<td>235</td>
<td>230</td>
</tr>
<tr>
<td>2,000 - 2,500</td>
<td>233</td>
<td>207</td>
</tr>
<tr>
<td>2,000 &amp; Over</td>
<td>309</td>
<td>258</td>
</tr>
</tbody>
</table>

* - Low sample
In summary, it can be concluded that a "Before" and "After" comparison based on travel demand by trips, as shown in Figure 8, is not illuminating, as trips express only part of travel behavior (*). However, basing the comparisons on travel distance, speed and mobility, reveals many new aspects and trends, and allows a better evaluation of the travel characteristics in an urban area.

4.3 While details of the data required for applying the UMOT process are now under preparation for the World Bank (17), they can be summarized, especially for "Before" and "After" studies, as follows:

(a) A relatively small sample of vehicle and non-vehicle owning households, at different income levels, should be interviewed at both periods; preferably, travel diaries for more than one day should be recorded, in order to decrease the traveler/household daily variations of the travel constraints;

(b) The relationships of daily travel distance and time per traveler vs. door-to-door speed; as well as the daily travel distance, time and cost, by mode, vs. income; should be derived;

(c) Flow-speed measurements, as well as public transport passenger counts, should be carried out at key points of the road network. These data will furnish the values for the Alpha-relationship, as well as independent checks of the passenger and vehicle kilometers of travel and mobility measurements derived from the home interview surveys;

(d) Trip purposes should be ranked by their trip time and trip distance, in order to derive the ranking of the perceived values of trip purposes; an expected - or planned - change in speed could then affect not only the daily trip rate, but also the proportions of trip purposes within the trip rate.

(*) While underreporting of trips can affect significantly the trip rate, it affects travel distance and time to a lesser degree, as unreported trips tend to be short.
In summary, the total daily travel distance, time and cost per traveler and per household are essential data, for two principal reasons: first, to serve as controlling totals for the analyses and forecasts of travel behavior; and second, to serve as the parameters that describe the total travel system, within which all the single travel components, such as trip rate, trip distance, trip time, proportions of trip purposes, and car ownership, interact with each other by trade offs.

* * *

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