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SPEED-FLOW RELATIONSHIPS FOR USE IN AN URBAN TRANSPORT POLICY ASSESSMENT MODEL.

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ABSTRACT

The increase in congestion and pollution levels in urban areas has resulted in the need to develop reliable and transferable methods of assessing the environmental and social impacts of transport pricing and other regulatory policies. In order to do this, it is necessary to quantify the marginal social costs of transport modes as a function of travel demand and then to obtain the optimum marginal social cost by the maximisation of utility subject to budget constraints. This approach is the basis for the development of an urban transport policy assessment model, being developed by a consortium led by the CES at the Catholic University of Leuven under the JOULE II Programme, which will be used primarily to provide a quantitative means of assessing external effects such as congestion, air pollution and noise.

This paper reports on the progress to date of the input of the Department of Civil, Structural and Environmental Engineering at Trinity College Dublin to this project where speed-flow relationships have been derived for peak and off-peak periods in Dublin using the SATURN network model developed in the Dublin Transportation Initiative (DTI). These relationships will be costed and used as an input to the policy assessment model at a later stage when a case study of Dublin is conducted. In order that the model can be easily transferred to other cities, methods are currently under investigation to address this, such as the inclusion of a measure of capacity in the speed-flow relationships.

INTRODUCTION

Increasing concern over congestion and pollution levels has resulted in the need to estimate the cost of both to the environment and to other transport users and non-users. At present, a car driver pays the resource costs of using a car i.e. capital costs, fuel costs, insurance costs etc. but does not pay for the delay the vehicle inflicts on other road users or the cost of damage caused by emissions from the vehicle to the environment. A controversial and politically sensitive solution would be to require vehicle drivers to pay these additional costs. Several issues need to be addressed before deciding on this as a solution or the level of cost to be imposed.

One argument is that the marginal cost of congestion should be paid rather than an average cost per vehicle. On this basis, in uncongested conditions an additional vehicle on the network will impose little delay, if any, on other road users and therefore the marginal social cost of delay to be paid by the driver would be minimal. On the other hand, in congested conditions an additional car on the network will increase the marginal social cost of delay significantly. In this case the driver has a choice; either to pay the marginal social cost of delay or to use another mode with a lower marginal social cost of delay. If an average cost was to be imposed on all drivers rather than the marginal social cost of delay under certain traffic conditions then this average cost might eventually be considered as a cost one must pay to run a car rather than as a factor in the choice of transport mode at a particular time.

On the issue of the cost of emissions to the environment and the means by which this should be addressed, different policies may achieve similar results. A driver could be simply charged for the marginal social cost of emissions from the vehicle where this cost would, for example, increase with increasing congestion levels. On the other hand, if stricter standards for vehicle manufacture are introduced which would mean 'cleaner' vehicles, the resulting higher resource cost of a more expensive vehicle would be balanced by a reduction in a lower marginal social cost of pollution to be borne by the car owner.

A strategic model (TRENEN) to address such issues is under development by the CES at the Catholic University of Leuven where the economics-based model will look for the optimal combination of price and regulatory policies in the energy-environment-transport domain by the optimisation of a welfare function. The TRENEN model will be for use at an aggregate, city level rather than link based as in network models. This presents difficulties particularly in the derivation of the relationships relating to traffic to be included in the model such as flow-delay relationships. However, it may be possible to include for disaggregation at a later stage.

The TRENEN model builds upon the work of Glaister and Lewis (1978) who developed a model to describe the variation in demand for three competitive modes: private car, bus, and rail. This model was used to derive optimal bus and rail prices with the assumption that car prices could not be varied. The TRENEN model will consider a greater number of transport modes and a fuller consideration of the social costs of these modes. The social costs to be considered by the model include vehicle congestion, pollution and noise costs and the regulating policies to be assessed will include transport pricing, different types of taxes, vehicle emission standards and fuel types.

The role of TCD in the model development includes:

1. The derivation of traffic level - delay relationships for Dublin for input to the strategic TRENEN model using a SATURN network model of Dublin.

2. The investigation into the best method of approximating traffic level - delay relationships for cities without network models.

3. A case study of Dublin using the TRENEN model where various transport policies will be evaluated.

4. An investigation into the possibilities of combining TRENEN and SATURN in city transportation planning recognising that each model addresses different questions. An example would be where the optimum marginal social cost obtained by TRENEN would be included in the SATURN network model so that the influence of external costs on route assignment could be evaluated.

The project is currently reaching the mid-term stage where TCD have completed the work outlined in points **1** and **2** above, on which this paper reports.

THE NETWORK MODEL OF DUBLIN

Dublin was modelled using the SATURN simulation and assignment model during the Dublin Transportation Initiative (DTI Final Report, 1994). The model developed covers two time periods representing a morning peak hour (08:00 to 09:00) and an off-peak hour (14:00 to 15:00). The network is modelled at two levels of detail; buffer and simulation. For the buffer links, a simplified representation of delay as a function of the flow on the link itself is used. In the simulation network, delay on the links is more detailed in that delays at junctions as a function of traffic control characteristics and of flows on all approaches are taken into account.

The simulation area has 776 junctions of which 443 are priority junctions, 320 are signalised junctions and the remaining 13 are roundabouts. In total this represents 2272 node to node links and 4764 simulated turns. The buffer network consists of 252 nodes and 381 links. Traffic is loaded onto the network through a trip matrix consisting of 367 zones. This trip matrix was determined through roadside interviews and matrix estimation techniques using traffic counts.

DEVELOPMENT OF CONGESTION FUNCTIONS FOR DUBLIN.

In a study undertaken for a Belgian urban area by De Borger et al. (1993), the marginal external cost of congestion was calculated by making three basic assumptions about the relationship between average network speed and traffic level. It was assumed that the average network speeds were 50 kilometres per hour (kph) for free-flow conditions falling to 30 kph at 5,600,000 passenger car unit kilometres (pcu.kms) and falling to 10 kph at traffic levels of 7,000,000 pcu.kms. Based on this information the following parabolic relationship was derived:

$$d = 6133949 + 138926\,s - 5232.1\,s^2$$

where d represents the total vehicle equivalent kilometres travelled in the city and s represents the average speed in kph at that level of travel.

Taking the inverse of this relationship the average time taken to travel one kilometre, t, as a function of the vehicle equivalent kilometres travelled can be obtained as follows:

$$t = {}^{1}/_{s} = \frac{10464.2}{138926.1 + (138926.12 + 20928.4 \cdot 6133949 - 20928.4 \cdot d)^{0.5}}$$

This relationship is plotted in Figure 1. The marginal cost of delay at any traffic level can be found by calculating the derivative of the function at that level.

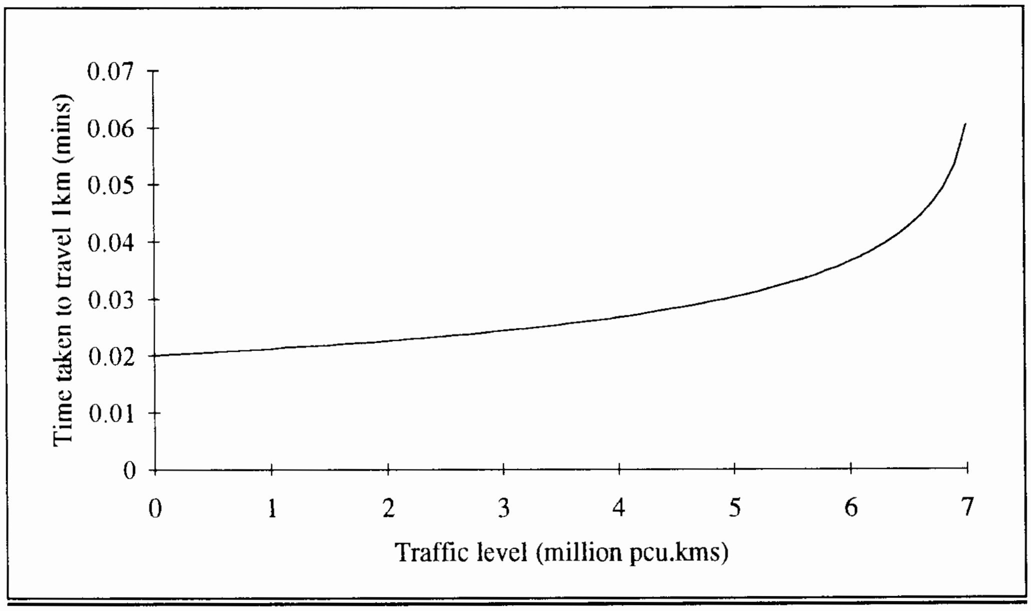

Figure 1. Traffic level -delay relationship used in De Borger et al. 1993

TCD's first objective was to derive a similar traffic level - delay relationship for Dublin. To maintain compatibility with the TRENEN model, a relationship in the units used by De Borger et al (1993) was considered to be the most suitable. However, a different method of deriving the relationship was used in the case of Dublin to that used by De Borger et al. (1993) because of the existence of the DTI network model (DTI Final Report, 1994).

A trip matrix factorisation method was used for the peak and off-peak periods, where each trip matrix was factored from 0.5 to 1.5, generally in steps of 0.1. The matrix at a factor of unity represents conditions in Dublin in 1991 (base year case). Multiplying the matrix by 0.5, for example, reduces the number of trips on the network by 50% whereas multiplying the matrix by 1.5 increases the number of trips by 50%. The model was run for each new matrix and the estimated total travel distance in million pcu.kms was extracted from the summary output of each model run. Traffic level was then plotted against time taken to travel 1 km at the traffic level represented by each matrix. The data for the peak and off-peak periods are shown in Figure 2. As the traffic level calculated is for one hour in the case of the peak and off-peak periods, then traffic level per hour could be considered as an estimation of traffic flow.

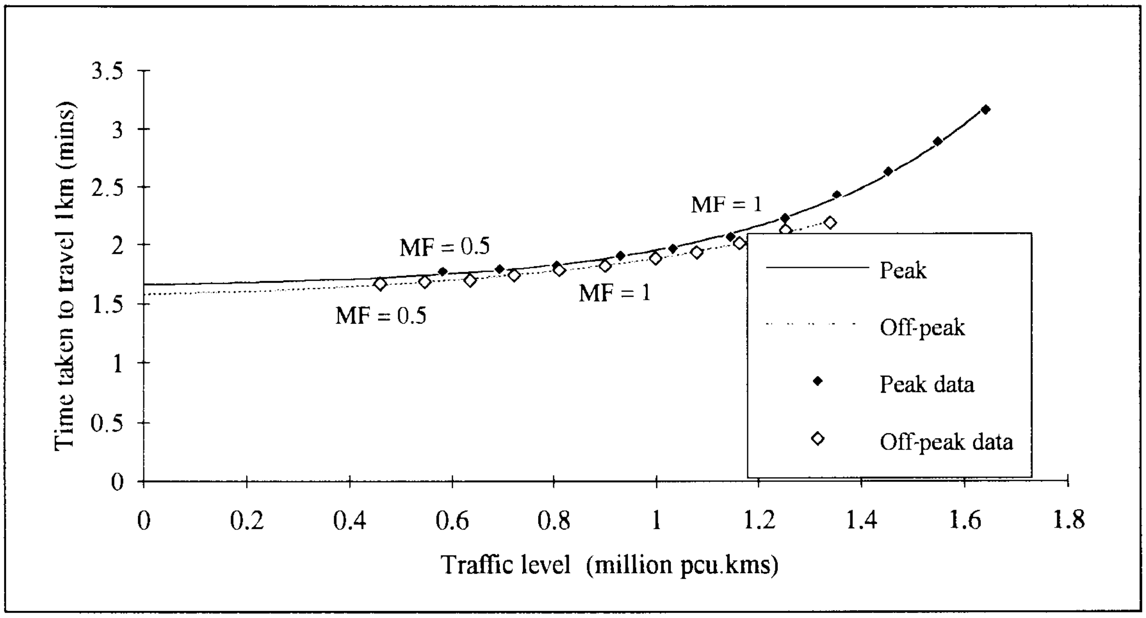

Figure 2. Influence of level of traffic on travel time in Dublin during peak and off-peak periods.

Note: MF refers to matrix factor.

The relationships appear similar for the most part, particularly at traffic levels below a matrix factor of 1, but some divergence at higher traffic levels can be noticed although when this divergence was tested statistically it was found not to be significant. A possible explanation for the divergence, however, would be that in the peak period traffic is generally concentrated on radial routes into the city and congestion occurs mainly on these links whereas during the off-peak period, traffic is more widely distributed as trip purpose tends to be more varied and therefore high congestion levels are less likely to occur under these conditions.

An inverse quadratic function of the type used by De Borger et al. (1993) was found not to a good fit for the Dublin data sets because at a certain traffic level, the function reaches a discontinuity. It was considered that this discontinuity might cause difficulties in the optimisation procedures in the TRENEN model so various mathematical functions were investigated to describe the relationships better, the best of which was exponential by nature and of the following form:

Peak: $t = 1.633 + 0.02625\, e^{2.486\,(d)}$

Off-peak: $t = 1.523 + 0.05739\, e^{1.833\,(d)}$

CONGESTION FUNCTIONS FOR SUB - AREAS OF THE NETWORK.

Dublin can be divided easily, both geographically and with respect to land use, into two distinct areas; the Central Business District (CBD) and an Outer Area, which is both residential and industrial. Figure 3 shows the CBD in relation to the simulation area and the entire study area which includes a combination of simulation and buffer networks.

The significant differences between the CBD and the Outer Area prompted a comparison between the traffic level - delay relationship for the CBD and that for the Outer Area and between the CBD and the total study area. The latter is the most interesting and this comparison is reported here.

Central Business District

The traffic level - delay relationships for the CBD for both the peak and off-peak periods are shown in Figure 4 and the relationships are as follows:

Peak: $t = 2.372 + 0.02357\, e^{30.51\,(d)}$

Off-peak: $t = 2.329 + 0.03815\, e^{22.60\,(d)}$

The trends in the plots are similar to those in Figure 2 but the scatter is higher. This may be due to the fact that the CBD is more sensitive to changes in traffic levels than the total study area. For example, if during a certain period traffic builds up and causes heavy congestion just outside the CBD, then the amount of traffic entering the area may be reduced. This phenomenon should consequently reduce delay within the CBD for that particular period.

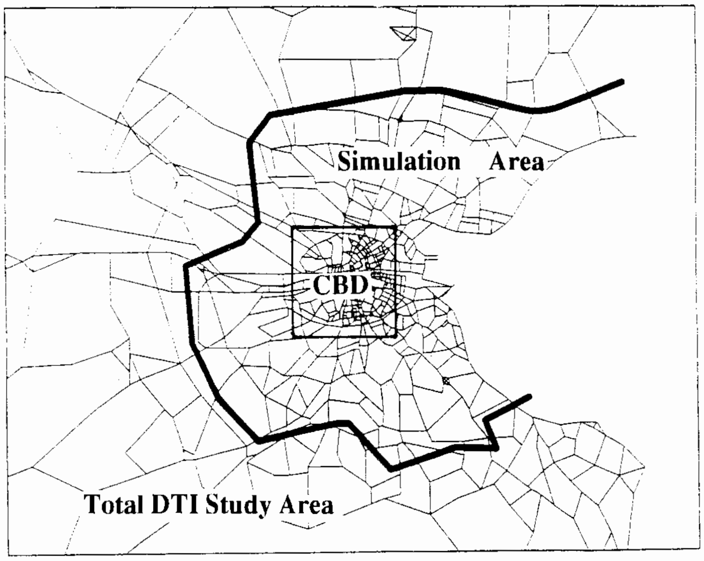

Figure 3. Location of CBD, SATURN model simulation area and the total DTI study area (DTI Final Report, 1994)

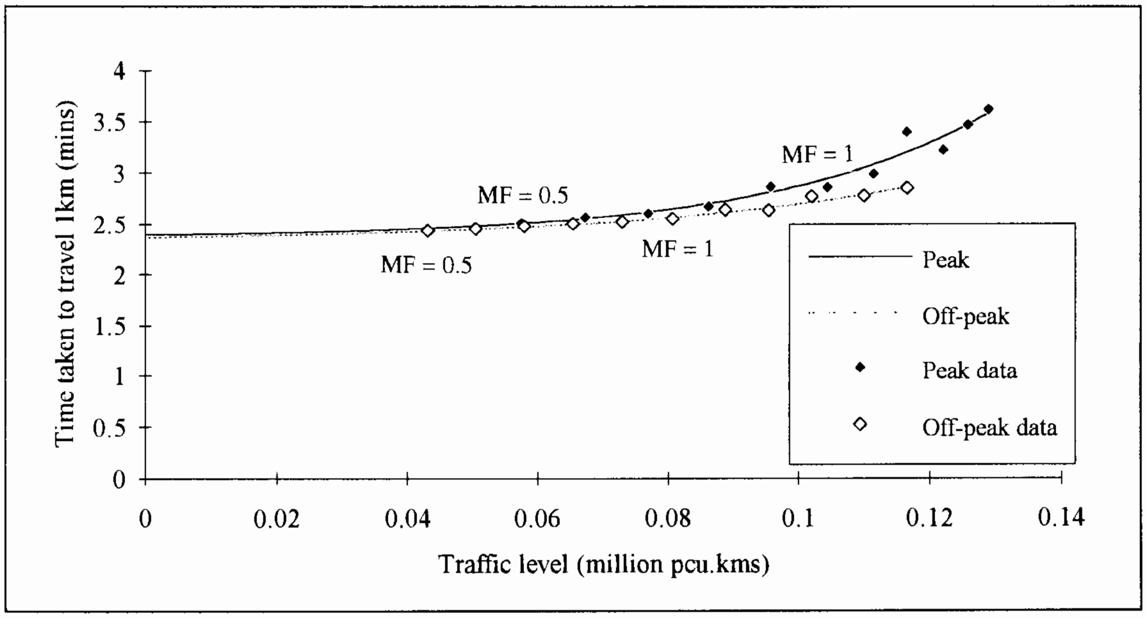

Figure 4. Influence of level of traffic on travel time in the CBD.

In order to compare the relationships for the CBD and the total study area more easily, the data is replotted in Figure 5 where traffic level is expressed per unit kilometre of network and termed travel intensity. It is considered that this method of presentation would also help in the ease of transfer of such relationships from one city to another. If delay in the CBD is compared with that in the total study area, significant differences are obvious even at low traffic levels. At a matrix factor of 0.5, the average time taken to travel 1 km is 2.5 minutes in the CBD compared with 1.77 minutes if the whole study is taken into account. CBD cordon counts done on a yearly basis by the local authority confirm that high levels of congestion, as expected, exist in this area during the peak period. In Figure 5 a gentler increase in slope at high traffic levels can be noticed. This reinforces the argument made earlier that the level of traffic entering the CBD is regulated by the level of congestion surrounding it.

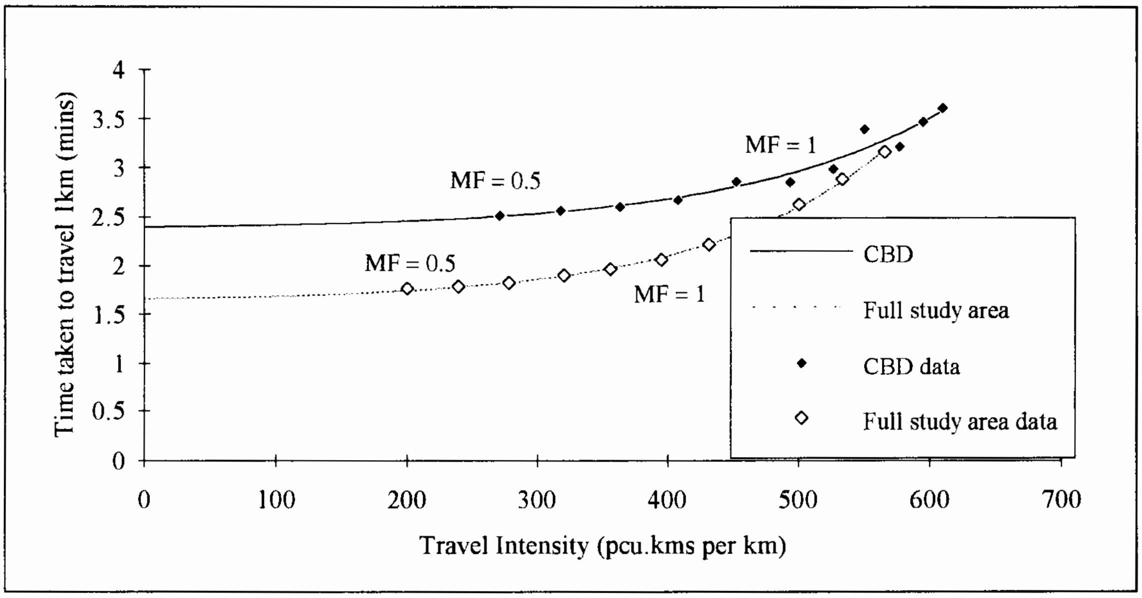

Figure 5. Travel Intensity - delay relationships for CBD and full study area.

SPEED - FLOW RELATIONSHIPS FOR OTHER CITIES

One of the main requirements cited for the TRENEN model is ease of transfer from one city to another. It is proposed that this will be handled by keeping the input functions both simple and of an aggregate nature. A disadvantage of this aggregate approach is that the local and network characteristics of traffic conditions cannot directly influence the marginal social cost of delay if an aggregate function such as a city - wide, traffic level - delay relationship is used to describe congestion. The marginal cost of delay calculated on the basis of the city traffic level - delay relationship would under estimate the marginal social cost of delay caused by traffic in the CBD. It is therefore suggested that at a later stage the model should be expanded before its application to real conditions to absorb such differences.

Accepting the aggregate nature of the model for the present, some other issues need to be addressed:

* Transferability of the exponential - type function to other cities

* Derivation of traffic level - delay relationships for cities without network models

Transferability of the exponential - type function to other cities

As an experiment, it was decided to conduct a similar analysis as that reported earlier for Dublin on another city, quite different in its layout and location to Dublin. A similar matrix factorisation method was used to produce a traffic level - delay relationship for Dubai using again a SATURN network model (supplied by Steer Davies Gleave). The relationships for the Dublin and Dubai simulation areas are compared in Figure 6. As before, the cruise speed of 50km/hr in Dubai can be found by calculating the inverse of the axis intercept. This is much higher than that of 32km/hr in Dublin. The higher cruise speed can be attributed to longer distances between junctions, wider lanes and a generally more generous layout of the network in Dubai. It may also be influenced by traffic regulations and driver behaviour.

An exponential - type function was fit to the Dubai data points obtained from the matrix factorisation, as can be seen in Figure 6. There appears to be more disparity between the curve fit and the data points in the case of Dubai although part of the curve for which delay is increasing rapidly fits the data points quite well. To improve the fit for the remainder of the data might involve splitting the function in two, perhaps, where one part of the relationship might be better represented as a linear function. An estimation of variance (R^2) of the exponential function to the data points was calculated to be 98.88% for Dubai compared with 99.4% for the curve fit to the Dublin data and was considered to be a reasonable fit for the purposes required. Notwithstanding this good result, it is planned during the case study of Dublin to conduct tests on the TRENEN model to determine its sensitivity to the function type used to describe the relationships i.e. test linear, exponential, combinations of functions etc.

The functions which were found to best fit the data in Figure 6 are as follows:

Dublin: $t = 1.908 + 0.0025\, e^{11.146\,(d)}$

(Note that this relationship is for the simulation area and is therefore different to that given for the total study area presented earlier)

Dubai: $t = 1.165 + 0.003\, e^{15.7\,(d)}$

In order to make the relationships more easily comparable, they are expressed as travel intensity - delay in Figure 7. In numerical terms, the cruise speed will not influence the marginal cost of delay, for which the functions are to be used, and so the relationships have been zeroed to aid comparison. It can be seen in Figure 7 that the Dubai network can cope with much higher levels of travel per kilometre than the Dublin network and this can be attributed to the characteristics of the network in Dubai mentioned earlier. The rate of change of slope as delay increases in both cities is similar although little can be interpreted from this without similar analyses on other cities.

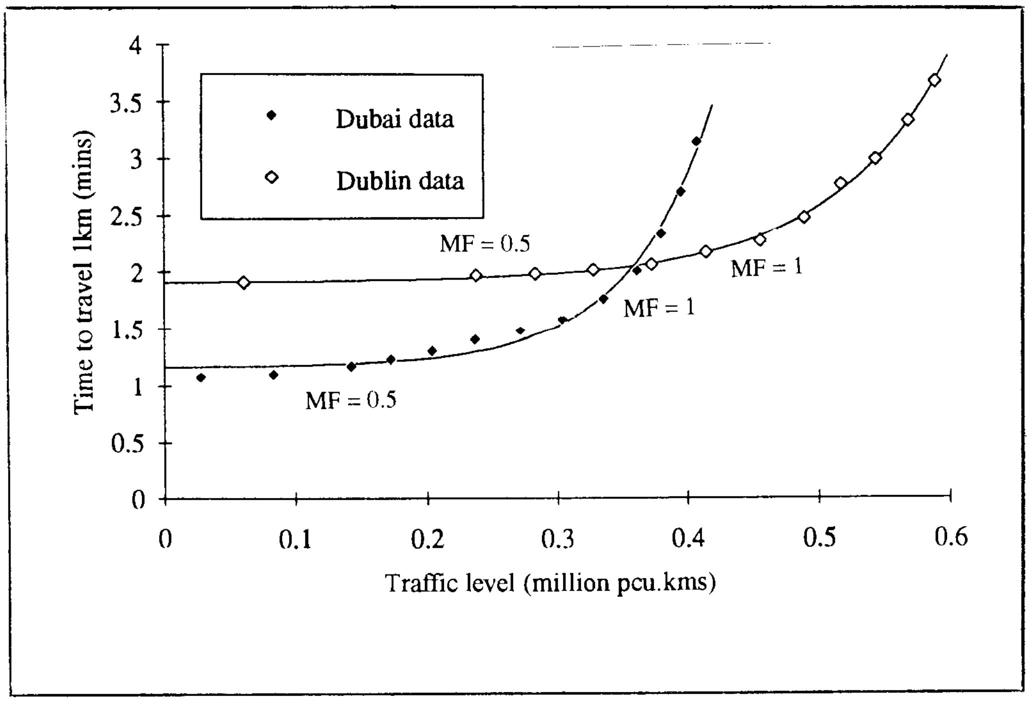

Figure 6. Traffic level - delay relationships for Dublin and Dubai

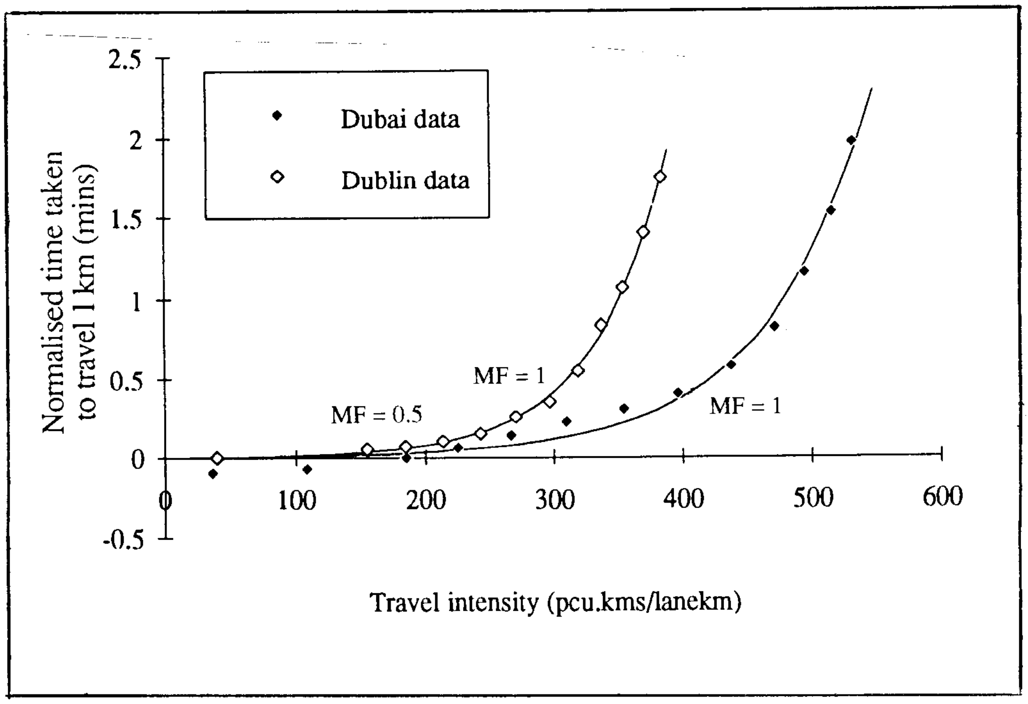

Figure 7. Travel intensity - delay relationships for Dublin and Dubai.

It is proposed at this stage of the TRENEN model development that an exponential - type function is possibly the most accurate for the description of congestion and is quite straight forward to derive for any city with a network model.

Derivation of traffic level - delay relationships for cities without network models

It was considered that if some measure of city capacity could be derived, the ease of transferability of the congestion functions to other cities would be better facilitated. The capacity of a city is difficult to define (Hills, 1993). It depends not only on the physical characteristics of the network but also on the trip pattern; a network serving mainly radial trips (to and from a dominant centre) will respond differently if it has to serve mostly orbital movements. The Dubai and Dublin travel time - flow curves in Figure 6 reflect these differences.

If a city capacity concept existed, then one would expect that the ratio of the city capacity of Dublin to that of Dubai would be similar to the ratio of the traffic level - delay relationship of Dublin to that of Dubai (refer to Figure 7). Methods of describing city capacity were investigated, the best of which appeared to be the sum of all turning movements at all junctions in each city during one hour. When the ratio for Dublin to Dubai was calculated, it did not bear any relation to the ratio of the flow - delay curves. This type of measurement is expensive even if city capacity could be described in an acceptable fashion and for the purposes required i.e. for use in an aggregate model, this expensive method would not be acceptable. However, if the analysis gave more favourable results, then simplification of the method would have been explored.

A more promising method of deriving traffic level - delay relationships for cities without network models would be to develop a simple methodology to make observations on each city at different levels of congestion. These observations could be easily made by the use of 'floating car surveys'. The main issue to be addressed is how to identify an appropriate set of links and times of day for undertaking these surveys. The representative sample of links should then be converted into floating car survey circuits for observation. This method could be conducted in a matter of weeks and at low cost. This data could then be used to re-calibrate the flow - delay curves already produced for Dublin to produce a traffic level - delay curve for the city in question.

CONCLUSIONS

This paper reports on the work to date conducted by TCD on the TRENEN project which ultimately aims to produce a transferable strategic model that reflects the cost of the environmental impact of traffic and which costs should be applied to vehicle users to achieve a balance between supply and demand by optimising welfare. The conclusions of the research reported in this paper are as follows:

1. A traffic level - delay relationship is required for each city to be modelled by the TRENEN model. The best means of deriving this relationship for a city with a network model is to factor the trip matrix to represent different levels of demand and to calculate the delay imposed for travelling 1 km on the network at each level. The function found to best describe the relationship between traffic level and delay is exponential in nature and monotonically increasing.

2. Two cities, Dublin and Dubai, were studied using the matrix factorisation method described in **1** above. The cities are quite different in layout but it was found that exponential - type functions fitted both relationships quite well. On this basis, it is proposed, based on the research so far, that the aggregate traffic level - delay relationship for a city can be best described by a function of this type.

3. The traffic level - delay relationship for sub-areas of Dublin were found to be quite different to that of the whole city and, as expected, delay was higher in the CBD. It is considered that the use of a city traffic level - delay curve may dilute the delay in specific parts of a city. Further disaggregation may be necessary before the model could be applied to real conditions.

4. It is concluded that a traffic level - delay relationship for a city without a network model can be best derived using floating car surveys. This would mean that delay at different levels of congestion could be observed. The exponential - type traffic level - delay relationship for Dublin could then be re-calibrated for the city using the observations.

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