PEAK-PERIOD PROPORTIONS IN LARGE-SCALE MODELLING

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The paper explains a method for predicting the proportion of trips falling within peak periods and describes some applications of the method within the Netherlands National Model. The key new element introduced is the forecasting of <u>changes</u> in the fraction of journeys that are made in the peak period as a result of changed congestion levels or as a result of time-of-day-dependent policy such as road pricing.

1. **Introduction**

The full evaluation of many aspects of transportation policy, whether concerned with infrastructure investment (e.g. new or widened roads) or other policy (e.g. "road pricing" or public transport improvements), requires the consideration of both 24-hour traffic flows and "peak period" flows. For example, traffic accidents, noise and pollution are caused by vehicles moving at any time of day or night, while, generally, traffic congestion is only or mostly present during the times of peak traffic flow. Thus it is necessary for full evaluation of policy to predict both 24-hour and peak period flows. In principle, weekend traffic should also be considered, but this is not current practice in The Netherlands.

The "classical" method of treating this problem in large-scale modelling is to attribute a more-or-less fixed fraction of the traffic flow to a peak hour and to make separate assignments of the traffic on 24-hour and peak-hour bases. Often a notional one-hour peak period is used as representative of both morning and evening, although traffic congestion may cover longer periods and directional differences are often large. The purpose mix of the traffic, which strongly affects the proportion of trips falling in the peak, is not always taken into account.

A slightly more advanced version of this method was used in early applications of the Netherlands National Model System (LMS), when pre-specified fractions of traffic *for each purpose*, separately for *outbound and homebound* *trips*, were attributed to each of *two-hour morning and evening peak periods* (these fractions depended on input assumptions about the development of working hours, holidays, etc., which are expected to affect peak-hour fractions for all travel purposes). Adjustments were made for the analysis of specific "bottlenecks" using an *ad hoc* model (Van der Hoorn and Van Hoek, 1988) that made allowance for "latent demand" - i.e. trips that would travel in the peak but are suppressed by current congestion levels.

However, particularly when congestion in peak periods may be high or when policy is intended to influence peak-period proportions, fixed factors are no longer acceptable. Subsequent LMS applications therefore used varying factors based on results from a preliminary market research study, while a more substantial research programme was sent in hand to obtain a more soundly based method for predicting changes in the factors.

It is the objective of this paper to report the results of that research programme and to describe how these results were incorporated into the forecasting models. Of particular concern are planning issues where the *capacity* of roads or other travel facilities is of central concern: i.e. where assignments must be made.

The following section discusses the approach of forecasting peak-period proportions by modelling travellers' choices of the time of day of travel; these choice models form the basis for the predictions of peak-period proportions. Section 3 shows how the choice of time of day can be integrated with the modelling of other travel choices (i.e., models of mode split, trip distribution and assignment) without excessively complicating the model or causing the calculation time to be excessive. A final main section looks at the integration of the travel demand model, extended by the introduction of the time-of-day component, with the "supply model" (i.e. capacity-restrained assignment) to find equilibrium in an iterative process. A summarising section gives some results that have been obtained from the LMS by the use of these methods and concludes on their practicality.

2. **Modelling the Choice of Time of Day of Travel**

Disaggregate modelling of travellers' choices has proved a valuable means for developing models to make aggregate forecasts of many aspects of traveller behaviour. In the LMS, disaggregate models of licence holding, car ownership, travel frequency and destination and mode choice form the basis of the aggregate forecasting system. For modelling changes in peak-period proportions, the disaggregate approach (i.e. modelling time-of-day choice) proved equally effective. Of course, like those other decisions, time-of-day choice presents its own specific problems and difficulties (see Small, 1982). Two of these should be mentioned.

First, it is unlikely that many travellers make decisions about the times of their outbound and return trips independently. The activities they have to perform at their destination have their own time constraints, such as the hours to be worked, the time it takes to complete shopping, etc.. If the outbound trip is delayed because of congestion or in response to policy, it is likely that the return trip will also be affected, even if the travel conditions at that stage of the day are not themselves altered. However, at present knowledge about these connections is simply not available in the representative quantitative form that would be needed for forecasting; the methods and models presented here are therefore methods and models for the choice of time of day of travel for a one-way trip, ignoring interactions with the timing of other trips made by the traveller.

Second, it is not immediately obvious how the alternatives facing the traveller should be represented. For some trips, departure times are constrained; for others it is the arrival time that is fixed. The relationship between departure and arrival is neither under the control of the traveller nor entirely predictable under congested conditions. Thus the choice actually made by the traveller may be to choose one of a large and uncertain number of alternatives, themselves possibly containing degrees of uncertainty. Clearly, for practical modelling it is necessary to make some simplifications.

In the context of choice of time of day for policy investigations when the capacity of travel facilities is of importance (typically, applications involving assignments), simplifications are forced in any case by the practicalities of the planning context. Traffic assignments under congestion can be produced only as the result of a procedure that is itself iterative. Moreover, as we shall see, the introduction of the time-of-day dimension increases the importance of obtaining an equilibrium between the travel demand and supply models: once more an iterative process. To avoid excessive amounts of computation in large-scale studies it is necessary to reduce the number of time periods for which separate assignments are made.

Note that the approximation of reducing the number of time periods for which assignments are made to a reasonable number from a computational viewpoint, typically 2 or 3, does not necessarily imply that it is assumed that the level of demand is constant within that period. Recent research on traffic flow and the meaning of the concept of the "capacity" of a road emphasise the stochastic nature of traffic flows. Variations can arise in the conditions of traffic flow from day to day for all kinds of reasons, from accidents to systematic seasonal fluctuation, while there can also be variation within the time period that is random or systematic. Providing the speed-flow functions, which are the key relationship in the supply model, are properly based on the concept of variable traffic flow there is no problem in modelling a longer period for which conditions are known to vary during the period itself.

For example, for applications within the LMS, work has been based primarily on highway assignments for three separate periods: morning peak, evening peak (each 2 hours) and the rest of the day (20 hours). It is known from the outset that conditions within each of these periods vary systematically, but this approximation in three periods was judged to capture most appropriately the total variation in conditions over the day, including the strong "tidal" flow differences between morning and evening peak, which also differ in other ways such as purpose split. The speed-flow functions were calibrated to be consistent with the selection of two-hour peak periods (Van Toorenburg, 1988).

A model is therefore required that can predict the changes in the peak-period proportions that are likely to result from changes in travel conditions in peak and off-peak conditions.

In principle, a model of time-of-day choice is needed to apply to all modes of travel (in the LMS, four modes: car driver, car passenger, public transport and "slow" modes). However, for some modes (car passenger, "slow") there is little interest in making detailed assignments, while the appropriate representation of travel conditions to influence time-of-day choice for these modes is not at all clear. For public transport, a model of time-of-day choice would be extremely interesting, involving the trade-off (for example) of over-crowding and frequency, but this would obviously require a major study. For the study reported here, attention was restricted to car drivers' behaviour and the trade-off of travel time (influenced by congestion), cost (e.g. road pricing) and changes in the time of travel.

At the outset, little quantitative information was available about the sensitivity of car drivers' time-of-day choices to changes in congestion levels or to other influences such as period-dependent road pricing which might cause them to change their behaviour. Research had however indicated that there was a significant suppression of demand by current peak-hour congestion, and that most of this "latent demand" was diverted to other travel times, rather than to other travel modes (Kroes *et al.*, 1987). A preliminary market research exercise confirmed that time-of-day choice appeared to be relatively more sensitive than (for example) mode choice, but this exercise was too small in scale to give the systematic representativity that was needed. A further market research exercise was therefore planned.

Fortunately, it was possible to integrate the needs of time-of-day choice modelling with a parallel study, being undertaken by The MVA Consultancy Ltd. (MVA, 1990), into some aspects of travellers' responses to road pricing. Their work included the derivation of trade-off results for non-business travellers on main roads in the Randstad for various road pricing levels and relatively low levels of congestion. Additional information was therefore particularly needed to cover higher levels of congestion and especially their impact on business travellers. Lack of resources and time precluded a full analysis, but, by planning the surveys to be done by Veldkamp Marktonderzoek in conjunction with the work they were also undertaking for MVA, it was possible to achieve a reasonable coverage of many important classes of travellers.

Stated preference questionnaires addressing the trade-off between changes in travel time and congestion delays were therefore designed and sent out to a sample of travellers. It is not possible in this paper to give a report of the conduct and analysis of these surveys, which is available elsewhere (HCG, 1990). To summarise the analysis, however, detailed models were developed for the likely response of business and commuting travellers to various levels of peak and off-peak congestion, including levels much higher than those current. These models give a comprehensive picture of the behaviour to be expected from these classes of traveller which is consistent with most of the (limited) other information available about time-of-day choice.

For application within the LMS, simplified models were derived that predicted the distribution of trips over the three time periods to be used in practical applications. Consistently with other data processing, a trip was defined to fall in a peak period if the mid-point in time of the trip fell within the peak period; otherwise trips were defined to be off-peak. The models represented the choices of business travellers under the influence of light or severe congestion; separate models were developed for home-based and non-home-based travel. The assumption was made that road pricing would not directly affect the time-of-day choices of business travellers. Additionally, from the parallel MVA study, simplified models were derived that represented the behaviour of private, non-commuter travellers, under the influence of road pricing or light congestion. For commuters, information was available from both sources: the models appeared to be reasonably consistent, allowing a single model to be developed that represented behaviour under heavy or light congestion as well as road pricing.

While the models derived from these surveys do not contain all of the information present in the full, detailed models that have also been developed from the same data, they do represent the main effects of:

- congestion (i.e., as peak-period congestion increases, peak-period travellers divert to off-peak travel);

- road pricing or other cost differences between peak and off-peak, which divert some non-business travellers to off-peak travel;

while distinguishing separate sensitivities of behaviour by:

- travel purpose (commuter, home-based business, non-home-based business, other); generally, "other" purpose travellers are most willing to divert;

- direction of travel (outbound, homebound);

- peak period (morning, evening); the evening peak appears slightly more susceptible to change than the morning peak.

Because of their incorporation of all of these effects, even these simplified models represent a substantial advance on the previous possibilities of modelling time-of-day choice behaviour.

3. **Integrating Time-of-Day Choice with Other Choice Models**

While it is of some interest to predict time-of-day choice as an independent issue, the value of these models can be greatly extended if they can be integrated with existing models of mode split and trip distribution. In the LMS, as in other modern forecasting systems, these models are set up in a disaggregate choice framework (Daly and Gunn, 1985).

To motivate the discussion that follows, consider what happens in conventional model systems when congestion is expected to increase in the peak period or when a peak hour road pricing charge is imposed. Typically, mode choice and distribution are modelled for home-work travel using peak period skims, while for non-work purposes off-peak skims are used. This would imply that all the commuters would incur the peak-period deterioration in their travel conditions, while none of the other travellers would suffer. Clearly, in reality, *some* commuters already travel off-peak and some would switch to off-peak travel to avoid a deterioration in travel conditions, while *some* non-work travellers do currently travel in the peak and would face the same alternatives as the commuters.

Thus the addition of the time-of-day choice to the model only throws into sharper focus the problem that already exists of choosing the appropriate measure for the level of service (whether time or cost) when that varies over the day. This is a familiar problem in model structure (e.g. the appropriate relationship of mode and destination choice), where measures have to be derived to represent the average level of service over a set of alternatives.

The solution that is generally proposed for forming this link between related models is the "logsum" measure, whose name is derived from its form

$$L_K = \log \sum_{k \in K} \exp V_k \qquad [1]$$

giving the average 'utility' (negative generalised cost) L_K over the whole set K of alternatives as a function of the utilities V_k of the separate alternatives k. In the present case, L_K would give the utility of travel over the whole day as a function of the separate utilities (say) V_1 for the morning peak, V_2 for the evening peak and V_0 for the off-peak.

The logsum gives a much better and more reliable measure of utility than many other measures, such as the simple weighted average. In the case where the choice models are of (generalised) logit form, it can also be shown that the logsum is the *only* correct measure of average utility (see, for example, Ben-Akiva and Lerman, 1985). But even when the models are not exactly of logit form, the logsum gives a reasonable measure of average utility. In the current case, both the models of time-of-day choice and the existing models of mode and destination choice were of the logit form, so that the issue of approximate use of the logsum does not arise.

Thus it seems natural to use L_K as a measure of the utility of a journey (averaged over the whole day) in the models predicting mode and destination choice.

However, it is first necessary to determine whether this structure is appropriate: whether it might not be preferable to form a logsum over the mode-destination choices as an input to time-of-day choice. Either structure is equivalent to representing the entire mode/destination/time-of-day decision by a "tree logit" model (Daly, 1982). In such a case, the appropriate choice of structure depends on determining which of time-of-day or mode/destination choice is the more sensitive: this is simply an empirical question. The previous market research, which addressed this issue fairly directly, had concluded that time-of-day was substantially more sensitive than mode or destination choice. The new data were not inconsistent with this structure, which is also in accordance with intuition. Thus the structure in which time-of-day alternatives are averaged to form the utility input to mode/destination choice was accepted. A sketch outline of the resulting model structure is shown in Figure 1.

For application in the LMS, there remained the substantial problem of implementing the calculation of equation [1] in a way that was consistent with the previously existing and intensively applied LMS mode/destination models and assignment procedures. The treatment of assignment is dealt with in the following section; interface with mode/destination choice was solved by the following transformation.

The logit model representing time-of-day choice (for a specific purpose, origin-destination combination, etc.) gives the probability of travelling *off-peak* as

$$p_0 = \exp V_0 \Big/ \sum_{k \in K} \exp V_k = \exp V_0 / \exp L_K \qquad [2]$$

<u>Figure 1: Outline of Model Structure</u>

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+------------------+
¦ Licence, Car &  ¦
¦ Frequency Models ¦
+------------------+
 V
+------------------+
¦ Destination-Mode ¦
¦ Forecast Models ¦
+------------------+
 V
```

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+------------------+
¦ Time-of-Day ¦
¦ Forecast Models ¦
+------------------+
 V
+------------------+
¦ Assignment ¦
¦ Procedure ¦
+------------------+
```

Equation [2] can be re-written as

$$L_K = V_0 - \log p_0 \qquad [3]$$

which expresses the logsum in terms of the off-peak utility and the off-peak probability only (any other period could of course have been chosen instead of off-peak). The use of equation [3] to calculate the logsum instead of equation [1] has a number of advantages.

First, for use together with the existing software, the fact that the logsum can be expressed as a single correction to the calculation of off-peak utility V_0, which was already incorporated in the software, meant that extensive re-programming of the mode-destination models was avoided.

Second, the models had already been calibrated to 24-hour base-year behavioural data (taken from the national travel survey (OVG)) using off-peak utilities. This meant that, effectively, the base-year value of ($\log p_0$) had already been incorporated in the calibrated modal constant. For forecasting, it was then sufficient to calculate the correction

$$d_f = - \log p_{0f} + \log p_{0b} \qquad [4]$$

where the second subscripts f and b indicate forecast and base probabilities of off-peak travel respectively. Recalibration of the models was therefore not necessary; this consistency was an enormous advantage, because of the large number of results that had already been obtained with the models.

Third, in terms of the computational requirement, the reduction of the calculations of equation [1] to the single correction [4] meant that the processing time and demand for fast storage space was minimised. In the practical situation of LMS applications, computer disk storage space represented a major bottleneck.

With this transformation, the model system as operated can be shown in more detail as in Figure 2.

Figure 2: LMS Model System with Time-of-Day Component

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+------------------+
¦ Licence, Car &   ¦
¦ Frequency Models ¦
+------------------+
 V
+------------------+
¦ Destination-Mode ¦-------------------<--------------+
¦ Forecast Models  ¦------<------+ ¦
+------------------+ +---------------+ ¦
 V +-¦ d_f Correction ¦ ¦
+------------------+ ^ +---------------+ ¦
¦ Time-of-Day      ¦---+ ¦
¦ Forecast Models  ¦-------------<--------+ ¦
+------------------+ ¦ ¦
 V ¦ ¦
+------------------+ +-------------------------+ ¦
¦ Assignment ¦     ¦ Time & ¦ Peak - Off-Peak ¦ ¦
¦ Procedure  ¦-->--¦ Cost +-----------------¦ ¦
+------------------+ ¦ Skims ¦ Off-Peak Only +-+
 +-------------------------+
```

Thus the 'skim' outputs from the assignment procedure are used in two ways. First, the *differences* between peak and off-peak conditions are used in the time of day models to predict the peak-period proportions for each origin-destination pair. Second, the *off-peak skims only* are used in the destination-mode models to obtain the 24-hour matrices by purpose and mode; the effect of peak-period conditions appears in the destination-mode models through the d_f correction.

It is also clear from the figure that the model can only be run iteratively. The inputs to the demand models (i.e. times and costs) are derived from a "supply" model that requires demand estimates as input. Moreover, the assignment procedure itself is iterative. The methods used to solve this problem and to retain reasonable computer times are described in the following section.

4. **Iterative Solution of Equilibrium Problem**

The iterative problem of the interdependence of supply and demand in transportation planning has of course been encountered before. In this case, however, the importance and difficulty of reaching a good solution were emphasised by the particular nature of the problem.

First, some of the scenarios under investigation with the LMS involved very large growths in traffic volume: "unchanged policy" was forecast to give more than 80% growth in kilometrage up to 2010 (Bovy and Gunn, 1989), while road capacities could not realistically keep pace with this level of traffic. Under scenarios of this type, congestion would become very severe, with major traffic jams an inevitable feature of peak-hour travel. Allowing for the feed-back effect of increased congestion, traffic growth of just over 70% was forecast. Travel time under such conditions becomes difficult to estimate and very sensitive to flow levels.

To cope with the modelling of over-congested networks (where demand exceeds road capacity), a special assignment procedure "Q-NET" had been developed (Hungerink, 1989). This method gives an improved representation of traffic movement in jam conditions and eliminates some of the excessive sensitivity due to inadequate speed-flow curves in those conditions. Q-NET was essential for the testing of the time-of-day models.

The second important characteristic of the models being studied here is that the demand model is also very sensitive to supply conditions. The choice of time of day is substantially more susceptible to change in response to changed traffic conditions than the choice of mode or destination, as noted above. With all three of these changes available, the overall sensitivity of travel demand is high, increasing the difficulty of finding equilibrium between demand and capacity.

Finally, the models of the LMS are obviously large in scale to cover the entire country. The network contains about 10,000 links (one-way), while the mode-destination models work for six travel purposes on 1132 zones and the time-of-day models for four purposes on 345 zones. Each of the three stages in the process requires several minutes of computer time. More seriously, the amount of intermediate data storage needed presented a serious problem for the computer system used.

Clearly, efficient solution methods had to be developed for each loop of the iterative procedure. Most progress was made with the time-of-day/assignment loop, which is also the novel feature of the system, and most attention is therefore given to that loop here. However, brief comment about the other two loops can also be made.

For the assignment loop, simple iterative methods were used, assigning a fixed fraction of traffic at each iteration. It was found that fixing the number of iterations to 12 gave reasonable results in terms of the convergence achieved, while not consuming too much computer time. A fixed number of iterations improved the internal comparability of the runs.

For the destination-mode choice/assignment loop, simple repetitive runs of the two models were used. This method appears to give reliable convergence but is of course time-consuming. Recent work has focussed on methods of improving the rate of convergence by carrying forward partial results from one iteration to the next.

For the time-of-day/assignment loop, a new method called the 'fictive cost' approach was developed. This method attempt to short-circuit the repetitive application of the two models by using the first runs to try to jump directly to the solution point. Its development was made absolutely necessary because simple repetitive applications gave *diverging* rather than converging results in some cases, but since the result is obtained in the equivalent of 2½ iterations it could be competitive even when repetitive applications gave reliable results.

The method is illustrated in Figure 3. Initial execution of the destination-mode models and the time-of-day model is made for off-peak conditions, i.e., in terms of 'generalised cost' differences, $C_0=0$, yielding a demand for a given period of T_0. This demand level can then be assigned, giving new generalised cost differences C_1. The process is then repeated, giving a series of equations which can be expressed analytically as

$$T_i = D (C_i) \qquad [5a]$$

and

$$C_{i+1} = S (T_i) \quad [5b]$$

for i = 0, 1, 2, etc., where D is the demand function given by the time-of-day model and S is the "supply function" given by the assignment procedure. These steps are illustrated in the Figure, where it may help to note that step [a] represents a vertical movement to intersect the demand curve, step [b] a horizontal move to intersect the supply curve. Five steps, roughly two-and-a-half full iterations, are shown, starting from the origin $C_0 = 0$.

In the diagram it is clear how repeated application of the two models might be expected to spiral in to the point of intersection of the two curves. Unfortunately, in practice, these steps are both too time-consuming and also liable to fail because of *divergence* of the process.

The method of 'fictive cost' has been developed to deal with this problem. This method attempt to find the optimum from the results of the first 2½ iterations, by finding the point of intersection of the straight lines joining the last pairs of points on the two curves. A little algebra shows that this point, also illustrated in the figure, is located at

$$C_F = C_2 + F . C_1 \quad [6]$$

where

$$F = (T_0-T_1) / ((T_0-T_1) + (T_2-T_1)) \quad [7]$$

It is clear that this "cost" C_F given by [6] is fictive in the sense that no driver has experienced it and that it may not be possible to achieve the combination of time and cost implied by the mixing of C_1 and C_2. For this reason, the method is always checked by making a full further iteration to ensure that the cost and demand level found at C_F is indeed the solution. Experience has shown that the approximation is good.

It will be seen from the figure that the approximate solution given by this method is exact when the supply and demand curves are straight lines. Also, the method of finding the solution on the cost axis minimises the error when the curves are convex on the same side, as shown in the diagram. In practice, it appears that the curves are nearly linear, while the shape of upwards concavity shown in the figure seems to be a reasonable expectation.

This method has been found to give reliable and reasonable results over a wide range of policy and exogenous variables.

5. Results and Conclusions

A method has been presented that allows the proportion of trips falling within peak periods to be forecast as a function of future travel conditions. The forecasting models are based on survey results. The models are integrated with the existing models, such as those of destination and mode choice of the Netherlands National Model (LMS) to give an overall traffic demand model incorporating time-of-day switching. Solution methods have been derived for the iterative problems that arise in this model system.

The model system constructed has been used to test a wide range of policy options involving time-period-specific road pricing and differing levels of congestion. While the system described here obviously requires more computer time and storage space than the simpler model used previously, it proved quite feasible to derive results within a reasonable time.

The LMS results showed clearly how the 'countervailing' effects of congestion reduction worked against the primary effect of peak-hour road pricing. Thus as peak-hour traffic is reduced by road pricing for commuter and other private travel, so speeds on the road increase, making travel once more attractive, particularly of business travellers with a high value of time. This effect is a very plausible demonstration of the existence of "latent demand" under the conditions prevailing in The Netherlands.

The conclusion for policy suggested by these results is that the effectiveness of a peak hour charge is limited in its total effect, and that the effect lies in reducing congestion, not in reducing kilometrage. If the environmental benefits of an overall reduction in kilometrage are required, then a substantial off-peak charge is also needed.

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