Monograph:
van Vuren, T. (1990) The Interaction Between Route Guidance and Signal Control: Development of a Multiple User Class Model. Working Paper. Institute of Transport Studies, University of Leeds , Leeds, UK.

Working Paper 318

Published paper

van Vuren, Tom (1990) The Interaction Between Route Guidance and Signal Control: Development of a Multiple User Class Model. Institute of Transport Studies, University of Leeds. Working Paper 318

Working Paper 318

December 1990

THE INTERACTION BETWEEN ROUTE GUIDANCE AND SIGNAL CONTROL: DEVELOPMENT OF A MULTIPLE USER CLASS MODEL

Tom van Vuren

FUNDAMENTAL REQUIREMENTS OF FULL-SCALE DYNAMIC ROUTE GUIDANCE SYSTEMS

The Interaction between Route Guidance and Signal Control: Development of a Multiple User Class Model

Working Paper 7

December 1990

Tom van Vuren

This work was sponsored by the Science and Engineering Research Council under a Rolling Programme.

Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT. England. Tel: Leeds 335325

Transportation Research Group, University of Southampton, Southampton, SO9 5NH, England. Tel: Southampton 592192.

Table of Contents

ABSTRACT

This Working Paper describes the development of a simulation model for route guidance, based on the principle of multiple user class assignment. The model calculates separate routes for guided and unguided drivers in full interaction with each other, assuming user equilibrium, system optimum and stochastic user equilibrium routing for each of the classes. As the model is equilibrium-based, it is most appropriate for the assessment of the long-term behaviour of route guidance systems. Conditions are derived under which the solution to the multiple user class assignment problem in a route guidance context is unique. The paper is finished with a literature overview of previous route guidance model work.

ACKNOWLEDGEMENTS

A great deal of input to the development of this route guidance model has been provided by Michael J. Smith, Dirck Van Vliet and David P. Watling. All the good ideas are theirs, but the errors are mine!

1 An introduction to route guidance

The continuing rise in car ownership and car use, together with a more environment-conscious viewpoint on, for example, new road construction, forces us to approach traffic management in new ways. In congested urban situations conventional control via one-way street systems and traffic signals is no longer sufficient. Fortunately, at the same time, developments in the electronics industry push forward new systems which could not even have been imagined by Leonardo da Vinci. One such system is electronic route guidance (throughout the report referred to as route guidance).

Examples of less advanced route guidance systems are conventional signposts and road maps. Problems with these systems are that they are static, become out-of-date quite quickly, and sometimes give incomprehensible or even wrong information. For an extensive overview of general guidance systems see (Robb, 1987). Electronic route guidance systems overcome these difficulties to a greater or lesser extent.
To some it may come as a surprise that tests with route guidance systems have been carried out since the early 1970s. In Japan the CACS demonstration project ran between 1973 and 1979 (Kobayashi, 1979). Although the results were encouraging, a full scale implementation was never carried through. Since then, most developments have been in static systems, which place most emphasis on map display. There was a general interest by car companies, for example Mercedes Benz in its NAVIGATOR project. A current large scale attempt to a dynamic guidance system is the ALI-SCOUT demonstration project in Berlin (Von Tomkewitsch, 1987). A similar study is being set up for London: the AUTOGUIDE system is expected to operate in a pilot version in 1991 (Belcher and Catling, 1987; Jeffery et al., 1987). According to the Second Transport Structure Plan, the Netherlands Ministry of Transport and Public Works also intends to introduce some kind of electronic guidance system (Ministerie van Verkeer en Waterstaat, 1988); interestingly, this system will in the first place be concentrated on trunk roads.

Two useful distinctions in route guidance systems can be made:

1. whether the system is static or dynamic. A static system **does not** update route information during the trip, whereas a dynamic system **does**. Both systems require an in-vehicle unit to display route information, but a dynamic system requires in addition road-side equipment, such as inductive loops or infra-red beacons (to send and receive data to and from equipped vehicles), plus a control centre to update travel information as it changes in time. An example of the first is the Philips CARIN system, based on CD-ROM technology; examples of the second are, for example, ALI-SCOUT and AUTOGUIDE, based on infra-red technology.
2. whether the system provides in-vehicle network information or route advice. Different countries seem to have opted for different ideologies with respect to route guidance, and particularly with respect to the type of information that is displayed to the driver. Whereas in Europe systems like ALI-SCOUT and AUTOGUIDE are developed, which will actually guide drivers to their destinations via directional advice at junctions, the Americans and the Japanese seem to favour in-vehicle information systems that display congestion levels and incidents, but leave the route choice decisions up to the drivers; an example is PATHFINDER (Blackburn, 1989). It has to be understood that both systems will have different properties as far as actual driver control is concerned. Guidance systems should allow us to determine equipped drivers' route choice to a certain extent in an explicit attempt to improve overall network conditions; with information systems we can only hope to increase drivers' information levels, so as to reduce their perception errors, and direct control cannot so easily be exercised. Both systems will also require different modelling approaches, as driver reactions to the systems are quite likely to be rather diverse.

In this report I will concentrate on dynamic electronic guidance systems, such as AUTOGUIDE, because of their greater topicality in the UK plus their greater opportunities for actual driver control. A system like this consists of:

- an in-vehicle display unit,
- a central control unit, and
- communications links between these.

An artist's impression of the London AUTOGUIDE system is given in Figure 1. The main task for the central control unit is to calculate optimum routes through the network, based on current information received from vehicles in the system plus historic data.

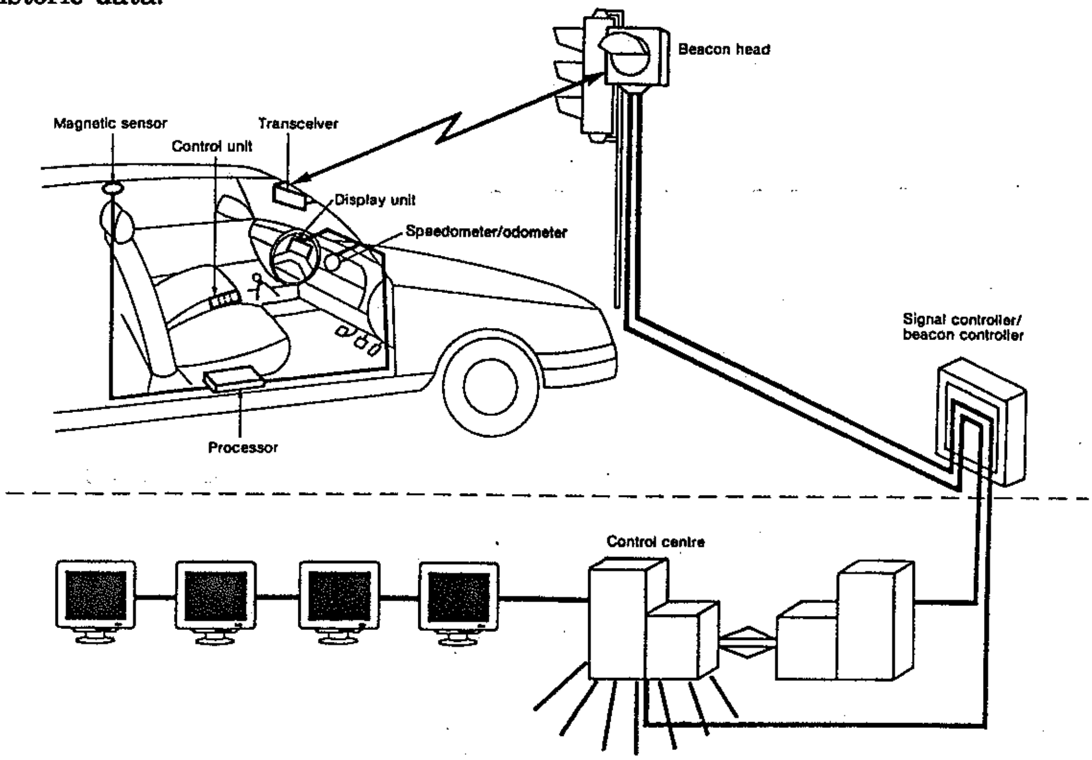

Figure 1 The AUTOGUIDE system (Source: Belcher and Catling, 1987)

Although current demonstration systems are based on single route advice between OD-pairs, the routing models will need to be considerably more complicated when levels of take-up of guidance in real-life systems become more than marginal. Such multi-routing will place extra strains on both communications and computations. As discussed in Van Vuren (1990a) the routing will need to become dynamic, taking into account the time-varying character of traffic, and the effect of re-routing on actual link travel costs will need to be anticipated.

In order to calculate optimum routes, the guidance system will need to possess knowledge about signal settings throughout the network. On the other hand, the system will receive flow information via the communications links with equipped vehicles and road side detectors. This flow information could be used to improve signal settings. We detect here a mutual influence between signal control and route guidance, similar to the interaction between traffic assignment and signal control discussed in Van Vuren (1990b and c).

However, whereas in the unguided situation we have to estimate (and accept!) drivers' route choice plus their reactions to changed traffic signal settings, in the case of route guidance we effectively have some control over the routing of drivers through the network. Proper mutually consistent route guidance and signal control offers a far wider scope for network travel time reductions than each of the systems in isolation, and could physically be achieved by a communications link between the route guidance control centre and the Urban Traffic Control centre. Modelling such an interaction is the subject of Van Vuren (1990d).

2. Route guidance as a case of multiple user class assignment

One of the basic implicit assumptions in standard assignment methods is that all drivers are identical; they do not differ from one another in either their travel cost definition or their vehicle size or vehicle performance.

Dafermos (1972) was probably the first to realise the limitations of this assumption, and to propose as a remedy a multiple user class (MUC) model that takes differences between drivers and between vehicles into account. These classes may differ in (Van Vliet et al., 1986):

- vehicle type/size;
- travel cost definition;
- network restrictions,

but within each class driver/vehicle attributes are identical. Typical classes could be lorries (particularly in conjunction with lorry bans), commuters (minimising some measure of generalised cost), business travellers (minimising travel time), and tourists (following road signs).

In a MUC assignment model all classes are to be assigned to the network in interaction with each other, so that in equilibrium **for each class** "no-one can improve his/her (perceived) travel cost by unilaterally changing route", and in that respect MUC assignment is clearly an extension to the standard, single class assignment model.

The relevance of the MUC concept for route guidance modelling is evident. In a situation with some kind of in-vehicle route guidance at least two user classes can be defined: those who are equipped, and those who are not. In fact we could even distinguish three groups, namely those who follow complete guidance, those who follow partial guidance (because they either lose their way or their confidence in the advice), and those who do not follow guidance at all. Each of these user classes would have a different cost definition, and possibly even different network restrictions (e.g. if the guidance network does not include all existing roads, for environmental or computational reasons).

We can distinguish a number of cost definitions for each user class, based on our representation of route choice in reality and the assumed routing criterion in the guidance system. A number of these are illustrated in Figure 2, and will be discussed next.

Figure 2. Multiple user classes with different guidance criteria

	A	B	C	D	E
guided	SO	UE	SO	SUE $\sigma_1<\sigma_2$	SUE $\sigma_1<\sigma_3$
unguided	UE	SUE	SUE	SUE σ_2	SUE $\sigma_2>\sigma_3$
partially guided					SUE σ_3

If we assume that drivers currently follow a Wardrop user equilibrium, and that the route guidance system will be employed to improve overall network conditions by pushing the route pattern of those we can control towards a system optimum (SO), situation A will occur; guided drivers are advised to follow routes with minimum marginal costs.

If, on the other hand, we believe that drivers currently make perception errors, which will be removed by the guidance system, a combination of stochastic user equilibrium (SUE) and user equilibrium (UE) assignment, as in case B, will occur. Along the same lines we could envisage a combination of guided drivers following a system optimum, and unguided ones following a SUE route pattern, as in case C.

Then, if we expect the system not to provide flawless information (because of communication delays or forecasting errors), the two classes could both follow a SUE, (case D), but the variance in randomised link travel times would be lower for the equipped vehicles. This representation could also be used for the modelling of in-vehicle information systems, that do **not** advise routes.

Finally, we could distinguish a third user class of those who follow partial route guidance; the complete driver population would therefore consist of three classes with decreasing level of errors in their route choice, based on an increasing information level (case E).

In summary, it is possible to model effects of a route guidance system via multiple user class assignment with a combination of system optimal, user equilibrium and stochastic user equilibrium drivers (with varying error terms over the classes).

The tool of MUC assignment now allows us to investigate the various future scenarios by comparing resulting network costs between different guidance strategies, and by changing the proportion of drivers per user class (representing the level of take-up of advice), the spread in link time errors (representing the quality of the advice) and the level of congestion, using real-life networks.

N.B. The magnitude of the error terms for each of the classes is actually less clear-cut than assumed here, for two reasons:

1. It is not certain that the errors made by those following partial guidance will be larger than the errors made by the system. Drivers may well recognise erroneous advice (caused by e.g. communication delays or an incomplete network description) and use their own knowledge, experience and insight to improve on the advice offered by the system.
2. The quality of guidance may be expected to increase with an increased level of take-up. More information from participating vehicles is then gathered, which will improve the accuracy of travel time forecasts. The assumption of fixed error terms is therefore a simplification.

3. Conditions on multiple user class cost definitions

Most of the work in the area of MUC assignment has been concerned with cost definitions for the respective classes and their influence on existence and uniqueness of an equilibrium solution; in addition solution algorithms have been developed. Here I will concentrate on the issue of cost definitions; algorithms will only be mentioned briefly.

The following notation will be used:

α_i	=	PCU-factor for user class i
m	=	number of user classes
n	=	number of links
f_{ai}	=	flow for user class i along link a
$\underline{f}_a$	=	$(f_{a1}, f_{a2}, \ldots, f_{am})$ = vector of class flows on link a
F_a	=	$\Sigma_i \alpha_i f_{ai}$ = total weighted flow on link a
$\underline{F}$	=	$(F_1, F_2, \ldots, F_n)$ = vector of total link flows
$\underline{F}^*$	=	$(F_1^*, F_2^*, \ldots, F_n^*)$ = equilibrium total link flow pattern
t_{ai}	=	$t_{ai}(\underline{f}_a)$ = cost for a vehicle of user class i of using link a, as a function of $\underline{f}_a$
$\underline{t}_a$	=	$(t_{a1}, t_{a2}, \ldots, t_{am})$ = vector of user class cost functions for link a

In the single user class case a separable link cost function is said to be one which only depends on the flow on that particular link. This definition is extended here for MUC, such that a user class link cost function is termed separable if it depends only on all the user class flows on that particular link, i.e.

t_{ai} is separable iff $t_{ai} = t_{ai}(\underline{f}_a)$

It is noted however that in some respects this is not a natural extension to the definition, since there is some similarity between a one-user class non-separable problem (in which the dependence is on flows on other links) and a MUC separable (as defined above) problem, and in fact this analogy motivated much of the work on MUC assignment. Unless otherwise stated we will only be concerned with separable cost functions (as defined above) in this report.

In Dafermos (1972) it is shown that for the case of continuous separable cost functions a sufficient condition for existence and uniqueness of an equilibrium flow pattern $\underline{F}^*$ is that the Jacobian J of link cost functions $\underline{t}_a$, given by

$$J = \left[\frac{\partial t_{ai}}{\partial f_{aj}} \right] \tag{1}$$

is symmetric for all a and positive definite. This would imply that user class i influences users of class j as much as user class j influences user class i.

The reasoning behind this approach is that condition (1) will make the MUC assignment problem one of convex minimisation, which has been well researched and for which efficient solution algorithms exist, as explained in Section 2.2.

An extension to this idea was introduced by Van Vliet et al. (1986). They employed a particular family of cost functions:

$$\begin{aligned} t_{ai} &= t_{0ai} + \beta_i d_a\,(F_a) \\ &= t_{0ai} + \beta_i d_a\,(\alpha_1 f_{a1} + \alpha_2 f_{a2} + \ldots + \alpha_m f_{am}) \\ &= t_{0ai} + \beta_i d_a\,(\Sigma_i \alpha_i\, f_{ai}) \end{aligned} \tag{2}$$

where:

t_{0ai} = class specific fixed link cost for link a

$d_a(\Sigma_i \alpha_i f_{ai})$ = standard flow-dependent link delay function

α_i = the person-car unit (PCU) value per user class; which expresses the effect on link congestion for each of the user classes, compared with a standard person car

β_i = class specific constant to express the valuation, per user class, of flow-dependent costs

For these cost functions condition (1) may be relaxed to the following condition:

$$\exists\ \gamma_i \quad (i = 1,2,\ldots,m) \text{ such that } \quad \left[\gamma_i \frac{\partial t_{ai}}{\partial f_{aj}} \right] \tag{3}$$

is symmetric and positive semi-definite for all a, and they showed that, if $d_a(F_a)$ is continuously increasing, condition (3) will be satisfied. The MUC assignment problem can then be solved via a diagonalisation approach as a sequence of standard single-class assignment problems.

N.B. Although the resulting total link flow pattern is unique with condition (3), this is not necessarily true for the flow patterns of the respective user classes (just like the resulting route flow pattern is not unique in the standard single user class case).

Due to the theoretical work by Smith (1979) and Dafermos (1980) it is now known that condition (1) is unnecessarily restrictive for the uniqueness of a MUC equilibrium. A milder, but sufficient condition for uniqueness is strict monotonicity:

$$(\underline{t}_a(\underline{f}_a) - \underline{t}_a(\underline{g}_a)) \cdot (\underline{f}_a - \underline{g}_a) > 0 \qquad \forall a \tag{4}$$

where the vector of cost functions $\underline{t}_a$ is continuously differentiable.

This is still a rather restrictive condition. If $\underline{t}_a$ is monotone (not **strict** monotone) a convex set of equilibria exists, which may consist of only one equilibrium. A way of testing for monotonicity is: for all links a the symmetrised Jacobian of link cost functions $\underline{t}_a$

$$\frac{J + J^T}{2} \tag{5}$$

is positive semi-definite (**though not necessarily symmetric**).

Daganzo (1983) considers a similar case to Van Vliet's, but his is more general in two ways:

(1) he employs non-separable cost functions (in that costs of using a particular link may depend on total flows on all links in the network);
(2) he includes the case of stochastic user equilibrium route choice in the MUC environment.

The family of cost functions Daganzo employs has the following general form (note the difference with Van Vliet et al. in (2)):

$$\begin{aligned} t_{ai} &= t_{0ai} + \beta_i d_a(\underline{F}) \\ &= t_{0ai} + \beta_i d_a(F_1, F_2, \ldots, F_n) \end{aligned} \tag{6}$$

where $F_a = \Sigma_i \alpha_i f_{ai}$ (again following the pcu-idea)

A unique solution with respect to link cost functions $\underline{t}_a$ to the MUC assignment problem exists if $\underline{d}_a(\underline{F})$ is monotonically increasing and continuously differentiable. Daganzo describes a solution algorithm based on the method of successive averages, as introduced by Sheffi and Powell (1982); see also Section 2.2. This algorithm is expressed in terms of link costs $\underline{t}_a$, but if the Jacobian of these cost functions is symmetric, an algorithm in terms of link flows F_a can also be constructed. It is evident that in the case of separable link cost functions (as I have defined them here) this condition is satisfied, as the Jacobian is a diagonal matrix. Furthermore, Daganzo shows that, if at least one of the classes follows a stochastic user equilibrium, the resulting MUC equilibrium is unique if for each link a the class-dependent link error terms ε_{ai} are mutually independent between classes, and independent of t_{ai}.

Recent research by Smith and Van Vuren (1989) investigates another family of cost functions for the situation of two user classes, consisting of three parts:

$$\left.\begin{aligned} t_{a1} &= t_{0a1} + (\gamma_{a11} f_{a1} + \gamma_{a12} f_{a2}) + d_a\,(\alpha_1 f_{a1} + \alpha_2 f_{a2}) \\ t_{a2} &= t_{0a2} + (\gamma_{a21} f_{a1} + \gamma_{a22} f_{a2}) + d_a\,(\alpha_1 f_{a1} + \alpha_2 f_{a2}) \end{aligned}\right\} \qquad (7)$$

where γ_{aij} = a link dependent constant to express the influence of the flow of user class j on the link costs for class i.

which in the linear (second) part allows for a more realistic interaction between classes than the pcu-idea of Daganzo and Van Vliet et al.; the first and third part are similar to the cost formulation of Van Vliet et al.

Monotonicity imposes certain conditions on the γ-values in the linear part of the cost functions, so that

$$\gamma_{a12} + K\,\gamma_{a21} \leq 2\sqrt{K\gamma_{a11}\,\gamma_{a22}} \qquad \forall a \qquad (8)$$

where $K = \alpha_2/\alpha_1$ (9)

Condition (9) is imposed by symmetry for the non-linear third part of the cost function.

An issue of importance, that has been recognised throughout MUC research is the unrealistic character of the assumption that the matrix

$$J = \left[\frac{\partial t_{ai}}{\partial f_{aj}}\right]$$

is symmetric for all a. Although the milder monotonicity condition does not impose this restriction, Dafermos (1980) argues that even monotonicity cannot always be established in a MUC environment, particularly when different vehicle sizes are involved. The work by Smith and Van Vuren (1989) is a first attempt to define conditions on such interactions between vehicles of different size. In a route guidance context, with vehicle sizes equal over the classes, this problem is only of minor relevance.

4. MUC cost definitions in a route guidance context

As described above, a route guidance system could be represented by a MUC assignment model. The model would consist of a number of classes for guided and unguided drivers, perhaps with network restrictions for the routes advised by the guidance system. The cost definitions are related to the assignment assumptions made for the equipped and non-equipped drivers, and as shown in Figure 2, these could be a system optimum (SO), a user equilibrium (UE) or a stochastic user equilibrium (SUE).

In this Section I will investigate properties of cost functions in a MUC route guidance context with drivers following SO, UE and SUE routes, that ensure existence and uniqueness of an equilibrium.
Throughout this report I will assume that guided drivers form a fixed proportion of the OD-matrix. The family of user class link cost functions used will be like the cost functions used by Van Vliet et al. (1986):

$$t_{ai} = t_{0ai} + \beta_i d_a (F_a) \qquad (10)$$

For simplicity's sake, let's call the actual average link costs t_a, the standard cost function:

$$t_a = t_{0a} + d_a (F_a) \qquad (11)$$

consisting of a fixed part and a flow-dependent delay term. These will be used as the actual link costs to determine optimum routes for classes that follow a UE assignment. Also, as only person cars are considered $\alpha_i = 1$ for all user classes, so that $F_a = \Sigma_i f_{ai}$. It is well known that system optimal routes can be determined by using the marginal link costs instead of the actual costs in route determination:

$$\begin{aligned} \check{t}_a &= t_a + F_a \, dt_a/dF_a \\ &= t_{0a} + d_a (F_a) + F_a \, dd_a(F_a)/dF_a \qquad (12) \end{aligned}$$

The marginal link cost function will only fit within the family of link cost functions (10) if

$$F_a \, dd_a (F_a)/dF_a = \rho d_a (F_a) \qquad \forall a \qquad (13)$$

with ρ a link-independent constant.

This may be re-written as follows

$$\frac{dd_a(F_a)}{d_a(F_a)} = \rho \frac{dF_a}{F_a} \qquad \forall a \tag{14}$$

so that

$$\begin{aligned} & d[\log d_a(F_a)] && = \rho \, d[\log F_a] \\ \Rightarrow \quad & \log d_a(F_a) && = \rho \log F_a + \log \beta_a \\ \Rightarrow \quad & d_a(F_a) && = \beta_a F_a^{\rho} \qquad \forall a \end{aligned} \tag{15}$$

Only a polynomial cost function with link independent power ρ, but variable parameter β_a satisfies condition (14). In that case

$$t_a(F_a) = t_{0a} + \beta_a F_a^{\rho} \tag{16}$$

$$\begin{aligned} \tilde{t}_a(F_a) &= t_a(F_a) + F_a dt_a(F_a)/dF_a \\ &= t_{0a} + \beta_a F_a^{\rho} + F_a \rho \beta_a F_a^{\rho-1} \\ &= t_{0a} + (\rho + 1) \beta_a F_a^{\rho} \end{aligned} \tag{17}$$

The system optimal drivers put more weight on the (flow and congestion related) variable cost component than their UE counterparts.

As stated before, a route guidance system can be modelled as a MUC assignment with drivers following SO, UE and SUE routes. Further, it has been established that if user class link cost functions of the form:

$$t_{ai} = t_{0ai} + \beta_i d_a(F_a)$$

are to be used, a polynomial flow-dependent delay part $d_a(F_a) = \beta_a F_a^{\rho}$ follows naturally. In a combined assignment of SO, UE and several classes of SUE drivers, will this cost function give rise to a guaranteed and unique equilibrium? User class cost functions for the m classes are:

for SO drivers $\quad \tilde{t}_{a1} = t_{0a} + (\rho+1) \beta_a F_a^{\rho}$ (18)

for UE drivers $\quad t_{a2} = t_{0a} + \beta_a F_a^{\rho}$ (19)

for all classes of SUE drivers $\quad t_{ai} = t_{0a} + \beta_a F_a^{\rho} \quad$ (i= 3,m) (20) where $F_a = \Sigma_i f_{ai}$ (as all pcu-values are 1).

It is evident that these cost functions satisfy Daganzo's condition (6) and that the resulting MUC equilibrium exists and is unique (if the error terms ε_{ai} for those classes following a SUE are mutually independent between classes and independent of t_{ai}).

5 Resulting flow pattern for a combination of SO and UE drivers

Above it was established that a combined flow pattern of UE and SO-drivers can be calculated. In this Section I will determine characteristics of such a pattern.
If two routes p and q serve both UE flow and SO flow between a particular OD-pair, the following condition must hold for the UE flow:

$$\sum_{a\in p} t_a = \sum_{a\in q} t_a \Rightarrow \sum_{a\in p} [t_{0a} + t_a(F_a)] = \sum_{a\in q} [t_{0a} + t_a(F_a)] \qquad (21)$$

For the SO flows, the following condition must also hold:

$$\sum_{a\in p} \left[t_a + F_a \frac{dt_a}{dF_a} \right] = \sum_{a\in q} \left[t_a + F_a \frac{dt_a}{dF_a} \right] \qquad (22)$$

For the cost functions stated in (18) this means that:

$$\sum_{a\in p} [t_{0a} + (\rho + 1)\, d_a(F_a)] = \sum_{a\in q} [t_{0a} + (\rho + 1)\, d_a(F_a)] \qquad (23)$$

Rewriting (21) and (23) gives:

$$\sum_{a\in p} t_{0a} - \sum_{a\in q} t_{0a} = \sum_{a\in q} d_a(F_a) - \sum_{a\in p} d_a(F_a) \qquad \text{(UE)} \qquad (24)$$

$$\sum_{a\in p} t_{0a} - \sum_{a\in q} t_{0a} = (\rho + 1) \left[\sum_{a\in q} d_a(F_a) - \sum_{a\in p} d_a(F_a) \right] \text{(SO)} \qquad (25)$$

Conditions (24) and (25) imply that there are only two situations in which two different routes p and q can each serve both UE-drivers and SO-drivers on a particular OD-relation:

1) $\rho + 1 = 1 \Rightarrow \rho = 0$

In this situation the power ρ in the polynomial equals 0, so that the cost function t_a contains no variable delay component. It is well-known that in such trivial circumstances the system optimum and the user equilibrium are identical, and equal to the all-or-nothing solution.

2) $\Sigma_{a\in p}\, t_{0a} - \Sigma_{a\in q}\, t_{0a} = 0$

This means that the two routes have identical fixed costs; then, also the summed variable costs must be equal for both routes, in order to satisfy conditions (24) and (25). Such circumstances do not usually appear in real-life networks.

Because the same calculation can be set up for any two routes in a network, this means that in practice **only one route for every OD-pair can contain both UE and SO drivers**. All other routes used will either contain UE drivers on this relation (with equal costs to the shared route, but higher marginal costs), or only SO drivers, and such routes will have equal marginal costs to the shared route, but higher actual costs. As system optimisers can only use routes with equal or higher costs to those routes used by user equilibrium drivers, their average costs will also be equal or higher (under the assumptions made here).
It is not possible to set up similar calculations for any other combination of routing assumptions, as in those cases at least one of the user classes will follow a SUE; the deterministic character of the SO/UE assignment which enabled these calculations, will then disappear.

6. Previous route guidance model work

Earliest reported route guidance related model work was carried out by Kobayashi (1979) who used a simulation model to assess possible benefits of the CACS route guidance system by comparing shortest routes for guided drivers with routes for non-guided drivers based on road length, number of lanes, percentage of trunk lanes and number of right and left turns. The network consisted of 99 intersections and 286 directional links; Kobayashi estimated a maximum **total** possible reduction in travel time in this network of 6%, at a level of take-up of 50-75%, compared with observed travel times in Tokyo.

Tsuji et al. (1985) set up a mathematical model, based on the stochastic nature of travel time, even under guidance. The proportion of guided vehicles was assumed so small, that no influence on non-guided vehicles was expected. Comparing the expected travel time of guided routes with those of alternative routes, they estimated an expected reduction in travel time for guided drivers of approx. 11%, which compared well with the observed reduction in the CACS system of some 12%.
Al-Deek et al. (1989) compared shortest route travel times with the observed route pattern using TRANSYT-7F in the Los Angeles SMART corridor, and found for recurring congestion travel time savings by route guidance of up to 12% (less than 3 minutes per trip of on average 25 mins length).
A similar approach was adopted by Rakha et al. (1989) who compared routes based on free flow costs (for unguided drivers) and those based on minimum costs (for guided drivers). These assumptions are clearly not valid in congested situations, which probably accounts for the possible total network travel time savings they recorded of up to 21%. An interesting finding of their simulations was, however, that a large proportion (85%) of total possible savings was achieved with the first 20% of equipped vehicles.

Breheret et al. (1990) used the heuristic dynamic assignment model CONTRAM (Leonard et al., 1978). They assumed unguided drivers to follow an approximate stochastic user equilibrium based on prevailing conditions, whilst guided drivers followed user optimum routes based on current conditions. If multiple routes were calculated in an attempt to find a user equilibrium re-assignment, guided drivers obtained travel time benefits of up to 15%; most of these benefits were obtained before a level of take up of guidance of 10% of the driver population. In this model the re-assignment of guided drivers benefited non-equipped drivers too with travel time reductions of up to approx. 4%. Finally, under these assumptions most of the total network travel time savings (of up to some 5% of total travel time) were achieved at a level of take-up of approximately 20% (a similar result was achieved by Rakha et al. (1989) with rather different model assumptions). If, however, re-assignment for guided drivers was calculated via a single, shortest route, total network travel times invariably increased, indicating possible problems with systems that advise single routes. Even when unguided drivers were allowed to re-assign because of the changed conditions, resulting network travel time savings of such a system were negligible or negative.

Smith and Russam (1989) also reported on a CONTRAM based model study, in their case of the possible benefits of AUTOGUIDE in London. Whereas unguided vehicles were assumed to base their routes on the average demand pattern and subsequent link costs, guided vehicles were routed along actual optimum routes (for a randomly perturbed trip matrix). They found an estimated average journey time saving of 6-7% for guided vehicles, which actually decreased with an increase in take-up. Unequipped vehicles benefited also by the guidance system, with travel time reductions of up to 3%, resulting in overall network travel time savings of 2.5-6.0%.

Koutsopoulos and Lotan (1989) assumed that route guidance would reduce the perception errors in link travel time estimates by participating drivers, so that their model consists of a stochastic user equilibrium assignment of two user classes with different variances in the (Normal) distribution of random perturbations in perceived link costs; these cost functions did **not** satisfy conditions for existence and uniqueness, as derived by Daganzo (1983). Scenarios they investigated on a 204 node network were: level of information (influencing the perception errors by guided drivers), percentage of take-up and the level of recurring congestion. Clearly, an increase in the quality of information resulted in a reduction in perception errors by guided drivers, and therefore in a reduction in their travel times. The advantage of guided drivers over unguided drivers in average travel time was roughly 4%, independent of the level of take-up, and an increase in congestion actually reduced their benefits of route guidance. Although these results are obviously rather limited, the most important finding by Koutsopoulos and Lotan is that in their model unguided drivers did not benefit **at all** from the improved route choice by the guided vehicles. This finding conflicts with the generally held belief (see e.g. Jeffery, 1987, and Smith and Russam, 1989) that route guidance benefits non-users too!

Another MUC assignment model was described by Van Vuren and Watling (1990). Unguided drivers were expected to follow a stochastic user equilibrium, whilst equipped drivers were guided via UE or SO routes, to which they adhered completely. The cost functions employed satisfied all conditions described in Sections 2 and 3 (see eqns 18-20), so that a unique and existing equilibrium (with respect to class-specific costs) was guaranteed. Tests on two real-life networks showed possible system benefits, expressed in total travel time reductions, of between 4% and 7%, with greatest benefits when congestion is high; c.f. Koutsopoulos and Lotan (1989). Further, the tests indicated the advantage of SO guidance over UE guidance, giving rise to greater travel time savings.

Not surprisingly, SO-routing primarily benefited the unguided drivers - at the expense of guided drivers - at lower levels of take-up. However, equipped drivers started benefiting too when their numbers increased: at the highest levels of take-up (over 50-70%) the results revealed how guided drivers under SO routing might benefit even more than the unguided ones. Routes with minimum marginal costs may be preferable to routes with minimum perceived costs (if the perception error is considerable).

Under UE-guidance the equipped drivers benefited most; as other authors had detected before, most benefits were attained with a very low level of take-up (less than 5%). In such circumstances unguided drivers hardly benefited at all, with travel time reductions for them always less than 2%, usually less than 1%, and in one case even negative!

For a corridor consisting of 3 parallel highways plus connecting links Mahmassani and Jayakrishnan (1989) built a model based on route-switching assumptions for drivers that receive in-vehicle dynamic network information. The main conclusions for this simple network were: for optimum resulting travel times both for the equipped drivers and for the system as a whole, route switching should only take place if the alternative route for the trip remainder is at least 20% shorter than the existing route, indicating possible instability problems for systems that guide via optimum routes (like ALI-SCOUT and AUTOGUIDE), as compared with systems that provide in-vehicle information (such as PATHFINDER). Secondly, benefits for individual drivers decreased with an increase in participation, whilst benefits for the system as a whole (generally) increased with such an increase; above 50% participation the increase in benefits was negligible.

The results of these various model studies are clearly rather ambiguous. Hypotheses about the route choice and interaction of guided and unguided drivers strongly influence the model outcomes. Often the models used in these studies are heuristic, or they are only valid under rather strong assumptions. This is not to belittle the importance of all these model studies: it merely shows the current problems in understanding and anticipating the expected behaviour of future route guidance systems.

The multiple user class assignment approach to route guidance modelling seems to be a sensible one. It allows us to investigate different behavioural assumptions per user class, though generally in an equilibrium context. That is not, however, a drawbwack in the situation of an interaction with signal control, which is the subject of this research. In Van Vuren (1990d) the development of such a MUC assignment/signal control model and test results from that model will be discussed.

7. REFERENCES

Al-Deek H, Martello M, May AD and Sanders W (1989) "Potential benefits of in-vehicle information systems in a real life freeway corridor under recurring and incident-induced congestion" *In: Proc of 1st Vehicle Vehicle Navigation and Information Systems Conference, Toronto, pp 288-291*

Belcher PL and Catling I (1987) "Electronic route guidance by AUTOGUIDE: the London demonstration" *Traffic Engineering and Control, Vol 28, Nº11, pp 586-592*

Blackburn R (1989) "PATHFINDER - a motorist information and road navigation system demonstration" *Paper presented at Engineering Foundation Conference on Traffic Control Methods, Santa Barbara CA*

Breheret L, Hounsell NB and McDonald M (1990) "The simulation of route guidance and traffic incidents" *Paper presented at 22nd Annual Universities Transport Studies Group Conference, Hatfield (unpublished)*

Dafermos SC (1972) "The traffic assignment problem for multiclass user transportation networks" *Transportation Science, Vol 6, Nº1, pp 73-87*

Dafermos SC (1980) "Traffic equilibrium and variational inequalities" *Transportation Science, Vol 14, pp 42-54*

Daganzo CF (1983) "Stochastic network equilibrium with multiple vehicle types and asymmetric indefinite link cost Jacobians" *Transportation Science, Vol 17, pp 282-300*

Jeffery DJ (1987) "Route guidance and in-vehicle information systems" *In Bonsall PW and Bell MGH (eds) "Information Technology Applications in Transport", Utrecht, VNU Science Press (Topics in Transportation)*

Jeffery DJ, Russam K and Robertson DI (1987) "Electronic route guidance by AUTOGUIDE: the research background" *Traffic Engineering and Control, Vol 28, Nº10, pp 525-529*

Kobayashi F (1979) "Feasibility study of route guidance system" *Transportation Research Record 737, pp 107-112*

Koutsopoulos HN and Lotan T (1989) "Effectiveness of motorist information systems in reducing traffic congestion" *In Proceedings of 1st Vehicle Navigation and Information Systems Conference, Toronto, pp 275-281*

Leonard DR, Tough JB and Baguley PC (1978) "CONTRAM: a traffic assignment model for predicting flows and queues during peak periods" *TRRL Report LR 841, Crowthorne*

Mahmassani HS and Jayakrishnan R (1989) "System performance and user response under real-time information in a congested traffic corridor" *Paper presented at Seminar on Urban Traffic Networks, Capri (I)*

Ministerie van Verkeer en Waterstaat (1988) "Second Transport Structure Plan" *Staatsdrukkerij, 's-Gravenhage (NL)*

Rakha H, VanAerde M, Case ER and Ugge A (1989) "Evaluating the benefits and interactions of route guidance and traffic control strategies using simulation" *In Proceedings of 1st Vehicle Navigation and Information Systems Conference, Toronto, Sept 11-13, pp 296-303*

Robb MC (1987) "Route information systems for motorists" *Transport Reviews, Vol 7, Nº3, pp 259-275*

Sheffi Y and Powell WB (1982) "An algorithm for the equilibrium assignment problem with random link times" *Networks, Vol 12, Nº2, pp 191-207*

Smith JC and Russam K (1989) "Some possible effects of AUTOGUIDE on traffic in London" *In Proceedings of 1st Vehicle Navigation and Information Systems Conference, Toronto, pp 207-287*

Smith MJ (1979) "The existence, uniqueness and stability of traffic equilibria" *Transportation Research, Vol 13B, Nº4, pp 295-304*

Smith MJ and Van Vuren T (1989) "Equilibrium traffic assignment with two vehicle types" *Paper presented at International Conference on Mathematics in Transport Planning and Control, Institute of Mathematics and its Applications, University of Wales College of Cardiff, and to be published in the Proceedings*

Tsuji H, Takahashi R, Kawashima H and Yamamoto Y (1985) "A stochastic approach for estimating the effectiveness of a route guidance system and its related parameters" *Transportation Science, Vol 19, Nº4, pp 333-351*

Van Vliet D, Bergman T and Scheltes WH (1986) "Equilibrium traffic assignment with multiple user classes" *Proceedings of PTRC Summer Annual Meeting, Seminar M, pp 111-122*

Van Vuren T (1990a) "Assignment issues of route guidance systems" *Proceedings of the 3rd IEE International Conference on Road Traffic Control, London, pp 23-27*

Van Vuren T (1990b) "Route guidance and signal control: an introduction" *Institute for Transport Studies, University of Leeds, WP 313*

Van Vuren T (1990c) "The influence of cost assumptions on properties of the combined assignment signal control problem" *Institute for Transport Studies, University of Leeds, WP 314*

Van Vuren T (1990d) "Route guidance and signal control: model results" *Institute for Transport Studies, University of Leeds, WP 319*

Van Vuren T and Watling DP (1991) "A multiple user class assignment model for route guidance" *Paper presented at the 70th Transportation Research Board Meeting, Washington DC*

Von Tomkewitsch R (1987) "ALI-SCOUT: A universal guidance and information system for road traffic" *6th International IEE Conference on Automotive Electronics, London*