A STOCHASTIC ROUTE CHOICE MODEL IN OPTIMAL CONTROL OF ROAD FREIGHT FLOWS: A MEXICAN CASE STUDY

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1 INTRODUCTION

The inefficiencies arising from increased freight road traffic in the late 1990s in Mexico have posed to planners engaged in the road provision the goal to find new control measures to reduce the adverse impacts, such as road damage and overloading. In the 1990s, road freight traffic in Mexico altered notably after the deregulation of the road freight industry in 1989; the North American Free Trade Agreement (NAFTA) in 1994; and the privatisation of the Mexican Railway in 1997. These changes created new land freight flows, attracting attention to the characterisation of lorry flows on the roads, and the estimation of possible impacts in areas like: route choice, road damage and repair costs, overloading practices and government’s decisions as weight limits, tolls levels and loading enforcement scheme.

In the Mexican case, there is a need for actions in freight traffic, and a first step is the yearly road survey promoted by the Mexican Transportation Secretariat since 1991, to gather freight lorry data on the paved road network (Rico, 1998). Interventions, however, need to be assessed before implementation, and this is the role for network modelling. The search for a realistic model based on the hauliers’ choices for routes suggests a stochastic focusing. This focus lets us represent hauliers’ choices, and their distinct perceived network attributes due to lack of perfect information, as well as coping with the problem of including in a model all the variables that could influence the utility in each choice (Kanafani, 1983).

2 RESEARCH AIMS

The research focuses on the interaction between the objectives of the carriers in moving the freight, and the planners (government) preserving the roads and imposing control measures. In this context, the objectives of each ‘player’ may not only be different but also could even be opposite. The aims for this research work are to show the preliminary results got in the modelling of hauliers’ route choices based on a stochastic perception of utilities in the routes, and the possible responses that planners have available to reduce the negative impacts of the traffic. Planners’ responses are related to the provision of quality road network through maintenance and repair actions, with subsidies or road charging being the
policy control variables used to influence hauliers’ choices. The immediate objective is to use the control variables to minimise the total cost of road maintenance, while anticipating the hauliers’ response to the control measures. The example used is one of the Mexican paved roads, and freight data come from surveys done by the Mexican Transportation Secretariat (Rico, 1998).

3 METHODOLOGY

A basic idea in the modelling for this research is the existence of several actors on the road network (simplified here to be planners and hauliers), each with their own objectives and performance measures. An equilibrated co-existence then implies that trade-offs need to be made. Nobody has an absolute control of the road network, but planners should aim for its rational use, encouraging flows on the appropriate links.

3.1 A simple example

Mexico City is a major origin for northbound freight flows. An intermediate destination is Queretaro, to the Northeast of Mexico City. Two possible routes exist to this city, as illustrated in Figure 1. Route 1 is a dual three lanes toll road and good pavement conditions; route 2 is free, but is single one lane and road quality may decrease in the rainy season. A typical daily vehicular freight flow between this origin and destination is 6400 (Rico, 1998).

![Figure 1. Route characteristics.](image)

Planners’ budget for road maintenance is limited, though they can have a proportion of the toll at their disposal. Seeking minimal spending, planners may persuade lorries to use the toll road through a subsidy scheme. Resulting savings in road maintenance due to the diverted traffic may then compensate or perhaps exceed the subsidies spent. The aim is to propose a subsidy scheme in order to minimise the total net cost of maintenance on both routes, while anticipating the potential responses of lorries to the toll level. Leaving aside the subsidy scheme, each toll level induces a certain flow splitting in the routes. For
simplicity of illustration in this example we shall use a logit binary route choice model. The relation utilised has been calibrated from a regression model derived from data from 30 Mexican toll roads (Rico, 1995):

\[
P_1 = \frac{1}{1 + e^{1.2 + 0.03(c_1 - c_2)}}
\]

where \( P_1 \) is the probability of choosing the toll road, \( c_1 \) and \( c_2 \) are the mean generalised costs on the toll and on the free road respectively, and a value of time=200 (near US$ 20.00) is assumed for pricing travel times on the routes. Damage cost calculations use the Standard Equivalent Axles SA10 of lorries, defined as: \( SA10 = \sum_k (Axle_k)^4 / 10^4 \), and assume the average value of 0.4 for the unitary cost of an SA10-km for the average vehicle (based on survey data). The model has two variables: \( T= \) the toll level, and \( S= \) the subsidy level. A fraction of 40% of the toll is assumed for recovering road damage cost, and following some simplification this leads to an optimisation problem of:

\[
\begin{align*}
\min Z &= (83.2 - 0.4T + S)f_1 + 125.2f_2 \\
\text{s.t.} \\
\quad f_1 &= \frac{6400}{1 + e^{1.2 + 0.03(T - S - 216.667)}} \\
\quad f_1 + f_2 &= 6400
\end{align*}
\]

where \( Z \) is the total net expenditure in road maintenance, and \( f_1, f_2 \) are the flows on routes 1 and 2 respectively. Fixing the toll (\( T=196 \), is the actual value), makes the optimisation problem dependent on \( S \) only. The resulting objective function, taking account of hauliers responses, is illustrated in Figure 2, where the optimal solution is seen to be \( S^* = 34.51 \), at which point the flows are \( f_1^* = 3916 \) and \( f_2^* = 2484 \).

Figure 2. Total Net Cost variation with subsidy.

In spite of the model’s simplicity, the fact that the optimal subsidy turns out positive suggests that the scheme can make sense in the policy-making field, as a possible measure
to be considered seriously. The resulting benefit is to motivate hauliers to avoid roads (e.g. the free road) that are more sensitive to damage, so avoiding higher maintenance costs.

3.2 General Network Case

In a general case, the road network can be seen composed of toll links and free links. Total net cost then is the damage costs over all the links plus the net effect of subsidy minus the toll fraction for maintenance just in the toll links. Constraints are used to represent the splitting induced by the probabilistic model governing the lorries choices.

The notation is defined as follows: \( Q_{rs} \) is the lorry flow from origin \( r \) to destination \( s \); \( K_{rs} \) is the set of paths connecting \( r \) and \( s \); \( v_a \) stands for flow on link \( a \); \( f_{ks}^{rs} \) is the flow on path \( k \in K_{rs} \); \( C_{ks}^{rs} \) is a random variable representing the perceived cost on route \( k \in K_{rs} \); \( T_k, S_k \) and \( M_k \) are respectively the toll, the subsidy and the toll fraction for maintenance in toll-route \( k \) and \( L_a \) is the length (kilometres) of link \( a \) inside route \( k \). In the subsidy scheme, if \( A \) is the cost of the SA10s of the average vehicle by kilometre, the optimisation problem for the planner is:

\[
\text{Min } Z = \sum_a A L_a V_a + (S_j - M_j T_j) V_a \tau_a
\]

s.t.

\[
P_k^{rs} = P\{C_k^{rs} \leq C_a^{rs}\}
\]

\[
f_k^{rs} = P_k^{rs} Q_{rs}
\]

\[
V_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{ak}
\]

\[
\sum_k f_k^{rs} = Q_{rs}
\]

for all link \( a \), route \( k \), toll-link \( j \), and all O-D pair \( r-s \) in the network. Both \( \delta_{ak}^{rs} \) and \( \tau_a \) are binary 0-1 variables; the former taking value 1 if link \( a \) belongs to path \( k \) from \( r \) to \( s \), 0 otherwise and the latter, taking value 1 if link \( a \) is a toll link, and 0 in other case.

For the sake of simplicity in this presentation, the average vehicle represents all vehicle types in the traffic. However, the model can be disaggregated by type of vehicle, basically distinguished by the number of axles. In the Mexican case, five types dominate the traffic flow: rigid lorries with 2 and 3 axles and articulated lorries with 5, 6 and 9 axles. This leads to five values for “A”, the cost of the SA10s each type impose by kilometre.

By substituting the constraints into the objective function, an unconstrained optimisation problem arises, which may be solved (in principle) by standard numerical algorithms. The most efficient such algorithms (quasi-Newton) require first derivative information, implying that among other things derivatives of the route flows with respect to the subsidies are required. Now, different models will arise from the problem above according to the distribution used for the perceived costs on the routes. Two well-known models for this task
are the logit model and the probit model. The logit model assumes that variations in perception of costs by road users are represented by a random error that is Gumbel distributed. This gives a tractable model both analytically and computationally, although it has some difficulty in dealing with correlated routes (paths sharing some common links), and so is not very realistic. The probit model assumes that variations in perception of costs by road users are represented by a random error that is Normally distributed, reflecting an additive effect of many factors influencing this perception. The well-known Central Limit Theorem supports the idea. The main advantage over the logit model is that the perception error can be specified for links, making path perception errors the sum of the relevant link perception errors. Hence the model automatically deals with the correlation/path overlap problem. This model, even though more realistic, lacks of a straightforward treatment, because it leads to a multivariate Normal distribution to consider the lorries’ route choices. While it has long been known that this difficulty can be overcome for estimating probit route flows by Monte Carlo simulation (Sheffi, 1985), only recently have efficient techniques been proposed for reliably estimating the derivatives (Clark and Watling, 2002).

4 PRELIMINARY CONCLUSIONS AND FUTURE RESEARCH

The proposed approach is opposed to the common practice of finding separately a user optimum (carriers’ point of view) or system optimum (planners’ point of view), but is instead based on mathematical models for dealing with multiple and interdependent objectives. The aim is to reflect in a more realistic way the intricate cumulus of actions and reactions observed in the hauling industry. The model presented in this paper considers only the interaction between road maintenance costs, tolls/subsidies and hauliers’ route choice, but will be extended to cover additional policy variables (e.g. fines for overloading, enforcement strategies), additional performance criteria (levels of service, congestion) and alternative responses of hauliers (eg. impacts on loading practices). This will be applied to data collected from surveys of the whole Mexican network.

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