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MODELLING PLANNER-CARRIER INTERACTIONS IN ROAD FREIGHT TRANSPORT: OPTIMIZATION OF ROAD MAINTENANCE COSTS VIA OVERLOADING CONTROL

Eric Moreno-Quintero[1], Tony Fowkes[2] & David Watling[2]
Corresponding author: David Watling, d.p.watling@its.leeds.ac.uk

Abstract – A bi-level modelling approach is proposed to represent the interaction between the vehicle loading practices of road freight transport carriers, and the decisions of a road planning authority responsible both for road maintenance and for the enforcement of overloading control. At the lower (reactive) level, the overloading decisions of the carriers impact on road maintenance expenditure, while at the upper (anticipatory) level the planner decides fine and enforcement levels by anticipating the responses of the carriers. A case study using data from Mexico is used to illustrate the method.

Keywords – Truck, Overloading, Bi-level Modelling, Mexico

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[1] Instituto Mexicano del Transporte, Apdo. Postal 1098, C.P. 76000, Queretaro, Qro. Mexico.

[2] Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, U.K.

1. INTRODUCTION

This paper will model the interaction of decision makers as actors in the freight transport system. In freight transport, the outcomes and impacts are influenced by many decision–makers, though far fewer than in the case of passenger transport. In recognising the presence of multiple actors (Fisk, 1986), a number of authors have turned their attention to an explicit representation of their behaviour, models being proposed with manufacturers, retailers and consumers as decision-makers (Nagurney *et al*, 2002; Nagurney & Toyasaki, 2005; Sheu *et al*, 2005; Figueiredo & Mayerle, 2008) and, more recently, third party logistics service providers (Panayides & So, 2005). However, one special form of actor often overlooked is the government or planner, whose decisions regarding regulations and pricing will influence the decisions made by other decision makers, and who indeed may make pro-active decisions that anticipate such influences on other actors. There are relatively few authors that consider the decision-making process of a regulatory/government body responsible for addressing the societal impacts of decisions taken by other players. Exceptions to this remark include, for example, the work of Chang et al (2007), who developed a decision-making tool for government agencies in planning for flood emergency logistics. Babcock & Sanderson (2006) investigated the impact on track and bridge maintenance costs of a change in policy to more economically efficient but heavier axle-load cars. Tzeng *et al* (2007) proposed an approach for planning relief delivery in the event of a major natural disaster, whereby the planner weighs up the potentially conflicting objectives.

In the present paper, part of a larger study, we shall focus on the particular issue of road maintenance costs and the impacts of vehicle overloading practices by freight transport carriers. Specifically, through a modelling approach, we examine the pro-active actions that may be taken by a planning authority responsible both for the recurrent maintenance of the roads and for the regulation of overloading, in order that (in the long-run equilibrium) the authority may cost-effectively and efficiently discharge its responsibilities on behalf of society. While this is an extremely important issue for policy-makers, articles on this topic appear relatively rarely in the formal academic literature, though this issue is evident in the wider, public-domain literature (ACSE, 2002; Dueker & Fischer, 2003; McKinnon, 2005; Knight *et al*, 2008; NVF, 2008).

The paper begins in section 2 by establishing the significance of road damage due to overloading, and the potential for its mitigation by enforcement policies. Drawing on this evidence, we present in section 3 a mathematical modelling approach for the control of overloading, which respects the *reactive* nature of the carriers' decisions while allowing the planner to adopt a higher level, *anticipatory* role when making strategic planning decisions. In sections 4 & 5, a case study based on Mexican data is used to illustrate the approach.

2. SIGNIFICANCE OF OVERLOADING, ROAD DAMAGE AND ENFORCEMENT

We begin our study by briefly examining the empirical evidence for the scale and impacts of the overloading problem for lorries (better known in some places as 'trucks'), and then move on to the role that existing enforcement procedures play. As a motivation for our subsequent modelling approach, we shall specifically examine the perspectives of the different 'actors' involved, in our case the carriers and planners.

From the road planner's viewpoint, overloading clearly generates serious impacts in the form of accelerated pavement wear and damage to bridges. Literature exists reporting both the prevalence of overloading practices and its resultant impacts. James *et al* (1987) and Harik *et al* (1990) both report on the effects of overloading on bridges in the USA. Specifically, Harik *et al* report on bridge failures from 1951 to 1988, where overweight lorries were recorded as the cause of total bridge collapse in 23 times out of 92 collapses. An OECD (1998) study across seven countries found up to 20% of vehicles to be overloaded in one of the participating countries (Finland), and up to 10% of axles in two countries (Italy and Germany). Road maintenance decision-making in developing countries was examined by Klockow and Hofer (1991) and Martinez (2001). In Mexico, overloading practices were recorded in a series of large-scale national surveys over the period 1991–2000 (Durán *et al*, 1996; Gutiérrez *et al*, 1999; Gutiérrez & Mendoza, 2000). In the period 1991–1997 the most serious cases were seen to be articulated six-axle lorries, where *average* overloading percentages of between 45% and 74% were recorded.

There is therefore ample evidence of widespread overloading practices. It is consequently necessary to consider the impact on road wear. From the well-known American Association of State Highways Officials (AASHO) road experiments in 1958–60 emerged the theory of road damage from axle weight as an n^{th}–power law, with $n \approx 4$ (Highway Research Board, 1962; Small, Winston & Evans, 1989; Cole & Cebon, 1991; TRB, 2007). The *4^{th}-Power Law* states that structural pavement damage for a given axle is nearly proportional to the 4^{th} power of the ratio of the axle load to a 'standard' axle weight (that standard varying between countries; for example, 8.16 tonnes in our case study country, Mexico). A commonly used measure for this damaging impact is the Equivalent Standard Axle Load (ESAL). For a vehicle with *m* axles, the corresponding *damage factor* in ESALs equals (assuming a standard axle weight of 8.16 tonnes):

$$Damage\ Factor = \sum_{j=1}^{m} \left(\frac{A_j}{8.16} \right)^4$$

where A_j is the j^{th} axle load in tonnes. In operational terms, the damage factor represents the equivalent number of passes of one standard-axle that would produce the same wearing effect as one pass of the lorry (Urquhart and Rhodes, 1990).

Although there has been debate concerning the appropriate value of the power in the equation for the damage factor (eg. Small *et al*, 1989), it is undoubtedly the case that the functional dependence of the damage with respect to vehicle weight makes the road repair costs very sensitive to goods vehicle overloading practices. By way of illustration, Table 1 gives the damage factors of several typical UK vehicles and their loads, assuming a 4th-power law. For example, by increasing from half to fully laden increases the damage factor more than five-fold for both a two-axle and a four-axle Heavy Goods Vehicle (HGV)

Vehicle type	Typical axle weights (tonnes)				GVW (tonnes)	Damage factor (ESALs)	Damage relative to family car
	Axle1	Axle2	Axle3	Axle4			
Family car	0.5	0.5	-	-	1.0	0.00003	1
Light commercial	0.5	1	-	-	1.5	0.00024	8
HGV 2-axles							
empty	3.06	3.06	-	-	6.1	0.039	1402
half laden	4.58	6.61	-	-	11.2	0.529	18792
full laden	6.1	10.16	-	-	16.3	2.709	96320
HGV 4-axles							
empty	4.0	3.2	1.7	1.7	10.6	0.085	3020
half laden	4.79	6.68	5.04	5.04	21.6	0.857	30464
full laden	5.58	10.16	8.38	8.38	32.5	4.836	171903

Table 1: Road damage impacts of several typical UK vehicles (from Urquhart & Rhodes, 1990)

In response to the severe effects noted of vehicle overloading, it is natural to ask what might be done by way of *enforcement* of legal loading limits. Many of the reports on overloading in the literature stress the fact that current enforcement schemes are inadequate to handle the problem. For example, Walton and Yu (1983) in a case-study from Texas (USA) estimated, for a 20-year period starting at the current conditions of their study, that extra costs resulting from overloading for the state would be $261 million, and only a fraction of this amount would be offset by the $84 million that would be collected from weight regulation enforcement.

From the viewpoint of the carriers, there is evidence that fine levels are too low to eradicate overloading, and instead they consider fines as another operation cost, to be traded off against other costs involved (Euritt, 1987). By way of illustration, Paxson & Glickert (1982) reported the effect of fine structures for three American states in the early 1980s, as indicated in Table 2, where the weakness of the enforcement schemes is manifest.

State	Maximal legal weight (lb)	Payload (lb)	Expected Benefit ($)	Expected Cost of Fine ($)	Net Incentive to Overweight ($)
Tennessee	73,280	80,000	245	3	242
Indiana	73,280	80,000	325	134	191
Iowa	80,000	90,000	425	180	245

Table 2: Effect of fines on overloading incentives (based on Paxson & Glickert, 1982)

Two basic parameters define the efficacy of an enforcement scheme: a) the inspection effort and b) the level of the fine. The former determines the probability of catching offenders, which multiplied by the latter, gives the expected fine that an overloading violator will face. The probability of catching violators varies from place to place, depending on the road network size and the resources available. For example, interviews with enforcement officials conducted by Paxson and Glickert (1982) gave estimates of apprehension probabilities of 5%, 20% and 15% for Tennessee, Indiana and Iowa respectively.

In conclusion, the interaction between the agents—the planner and the carriers—in the overloading issue is explained by each party aiming to minimise their own costs. The road planner is the proactive party, anticipating the carriers' reactions to the possible deterrent actions taken by the planner. To reduce overloading, the road planner implements a penalty scheme, determining a fine and a probability of detecting violators. Given the tonnes to lift and the trip distance, determined either by the market or by logistics needs, the carriers—the reactive party—choose the amount to load their vehicles, aiming to minimise the transportation cost including any expected fines to be paid. The fines collected from the remaining violators also partly offset the planner's expenditure on road maintenance, yet enforcement is itself a potentially expensive task, the cost of which must be balanced against its positive impacts in reducing road wear. In the remainder of this paper we aim systematically to capture these influences and potentially conflicting objectives of the carriers and planner, through a mathematical modelling approach.

3. BI-LEVEL MODELLING APPROACH TO OVERLOADING CONTROL

3.1 Problem formulation

The evidence presented in section 2 establishes the case for a strategic planning tool to assist the planner in making efficient, anticipatory decisions regarding the balance of effort devoted to loading enforcement and road repair costs. A strong theme running through section 2 was the presence of multiple objectives, the planner's primary interest in the costs of road maintenance and overloading enforcement, with some recompense available through fines collected, and the carriers' loading decisions being motivated by their own individual economic considerations, including vehicle operating costs, and the possibility of incurring fines for overloading. We thus need, as a minimum, a mathematical approach for dealing with problems with multiple objectives.

Looking to the literature, several potential mathematical approaches may be found for addressing such a problem, in related fields. Hu *et al* (2002) considered hazardous waste applications, proposing a problem in which government regulations were represented as *constraints* to a cost minimisation problem. In a similar technical spirit, Nozick (2001) considered generic facility location problems, where the objective is to minimise cost while satisfying some minimum level of service, with the desires of consumers (level of service) represented as a constraint. Likewise, Jula *et al* (2005) considered optimal routing of container lorries including so-called 'social constraints', which are enforced by the carriers to ensure that drivers do not work beyond a certain amount of hours per shift. Chang et al (2007) proposed a stochastic programming problem with capacity constraints for emergency logistics planning. In contrast to the focus on constraints, Korpela *et al* (2001) adopted a weighted optimisation approach, with a single objective function optimized that balances customer service with environmental performance. Tzeng et al (2007), on the other hand, avoided the need to pre-define weights, proposing a fuzzy logic-based, multi-objective optimization approach, whereby the planner weighs up the potentially conflicting objectives of minimising total cost, minimising total travel time and maximising minimal satisfaction.

The bi-level approach we propose to adopt is quite different to the above approaches, being neither based on (single level) multi-objective optimization nor on the representation of conflicting requirements as constraints. Past work in related fields that has relevance to our approach is now considered. Brotcorne *et al* (2000) adopted a bi-level programming approach to a freight tariff setting problem, where the 'leader'—with an upper level objective of revenue maximisation—is one among a group of competing carriers, and the 'follower' is a shipper with a lower level objective of minimising transportation cost. Kara & Verter (2004) also adopted a bi-level approach for selecting network links available to carriers of hazardous materials. In this problem, the 'regulator' minimises an upper level risk-based objective in terms of population exposure, and carriers at the lower level choose routes to minimise total transportation cost. Castelli *et al* (2004) proposed a bi-level linear program formulation of a two-player Stackelberg game between a 'shipper', minimising a lower level objective of transportation cost, and a traffic authority applying some form of regulation to an upper level objective which seeks to maximise the flow through the subset of links under the authority's control. In the same game-theoretic spirit, Nagurney *et al* (2002) and Nagurney & Toyasaki (2005) proposed a joint equilibrium model of three groups of non-cooperative actors, representing manufacturers, retailers and consumers.

For the problem considered in the present paper, we adopt a long-run equilibrium approach suitable for strategic planning, which is based on bi-level programming. We believe that such a bi-level formulation most closely reflects the decision-making hierarchy desired, in terms of allowing the planner to apply pro-active policy measures, as well as reflecting the differing levels of predictive ability available to the planner and the carriers. While it is reasonable to expect the planner to be able to anticipate the impact of loading enforcement measures on the carriers, it seems difficult to believe that individual shippers can anticipate the impacts of their loading decisions on the planner's policy. Thus, it is natural to associate the planner as a 'leader' and the carriers as 'followers', in game theoretic terms.

Thus it remains to set out the specific approach proposed to the overloading control problem. The relevant lower and upper level objective functions are first defined in sections 3.2 and 3.3 respectively, before describing the overall bi-level programming approach in section 3.4.

3.2 Lower level objective: The carriers' objective

Based on the framework proposed, the main purpose of the lower level model is to describe the responses of freight carriers to changes in enforcement and fine levels. While there may in practice be a multitude of responses, we shall focus on the decision of how heavily carriers of a given class choose to load their vehicles. Such a focus, we believe, is justifiable taking into account the focus of the study, namely the impact of heavy axle loads on road damage. We do not, therefore, consider decisions such as routing of vehicles, perhaps to avoid likely locations of weigh-stations, or longer-term decisions for a carrier such as fleet composition. If such decisions are deemed important, then they could be accommodated within the modelling approach by some kind of hierarchical decision model.

We suppose that the product is of sufficiently high density that volume constraints of the vehicle are not a factor, even when significantly overloaded in weight. Therefore, as volume considerations are immaterial, we shall refer to the decision variable for the carriers as the *load factor*, defined as the ratio of the tonnes carried to vehicle capacity, given a specific commodity and vehicle type for transporting the load. Once the carrier knows the loads to move and the trip distance, the load factor chosen will determine the cost per Tkm (tonne-km). It is supposed that the carrier will not waste vehicle capacity, so the assumed load factor is at least one. Private carriers will try to minimise this cost per Tkm, as will for-hire carriers in order to improve the total trip profit.

Now in the problem considered, there are many instances in which *either* the factors affecting the carriers' decisions *or* the factors affecting the planner's objective function may differ substantially between carriers (or even between different movements made by the same carrier). Examples of such factors include the payload capacity of the vehicle (offering the potential to overload), the axle configuration of the vehicle (impacting on the road damage effect of a given load), the suspension type of a vehicle (again affecting road damage impact), the operating costs/efficiency of particular vehicle types (affecting trade-off with fines), the commodity type (packaging shape, density, etc.) being transported (with volume and packing constraints/considerations affecting overloading potential and operating costs), the distribution of load over the axles affecting road-wear (varying by vehicle and commodity type), the distance the commodity must be transported (affecting the potential to detect overloading), and the pavement characteristics over which the commodity is transported (based on wear vulnerability).

While it may be desirable to reflect all such differences, in practice the availability and cost of collecting such data will inevitably limit the number of such dimensions for which the impacts may be distinguished. In order that the approach has maximum generality, and so can be tailored to the particular data availability of each case, the model proposed is developed around the notion of a *class*. Each class represents a particular combination of all the attribute dimensions that the modeller may wish to distinguish. Therefore, throughout the presentation of the model to follow, we shall define which attributes may vary by class, and allow the precise definition of a class to be made when any case study of the method is made (such as the one in sections 4 and 5).

Thus consider a carrier of a specific class k (k = 1,2,…K) moving T_k tonnes (where T_k is many times the capacity of a single lorry) over d_k kilometres, and define:

L_k = lorry's payload capacity (legal full-laden payload)

E_k = cost per km of an empty movement

x_k = load factor used (the load to capacity ratio)

$V_k(x_k)$ = vehicle operating cost per Tkm, a function depending on x_k

p_k = probability of catching an offender on any randomly-selected trip of class k

F = fine (monetary units) per tonne in excess of the payload capacity

w = the number of inspection points.

Then the expected cost for a carrier of class k, , is:

C_{1k} = vehicle operating cost + empty movements cost + expected fine.

In our model we shall assume that the penalty level for overloading is a sliding scale that is proportional to the amount of overload. Real systems will be discrete; even at their finest level they will only vary to the nearest penny/cent/dollar/pound. What we are doing in our model is an approximation to such a system. Our model will serve as a good approximation to the discrete system if there are many payment steps, but not so good if there are only one or two steps. In this latter case the method we have proposed could readily be used with a predefined step function replacing the linear function. Since in the end we propose examining fine levels on a discrete scale (see section 5.3), this change would make no material difference to the methodology. For simplicity, to be consistent with the strategic planning nature of the method we propose, we have decided to retain the simple assumption of a continuous sliding scale.

We are considering a case of bulk movement of materials, in which case the lorries will either be fully loaded, or overloaded. Since the operation requires $\frac{T_k}{x_k L_k}$ vehicles, the expected cost for the carrier is thus:

$$C_{1k} = \frac{T_k}{x_k L_k}\left[x_k L_k d_k V_k(x_k) + d_k E_k + (x_k - 1)L_k p_k F\right] \qquad (x_k \geq 1) \qquad (1)$$

which may be simplified slightly to:

$$C_{1k} = T_k\left[\left(V_k(x_k) + \frac{E_k}{x_k L_k}\right)d_k + \left(\frac{x_k - 1}{x_k}\right)p_k F\right] \qquad (x_k \geq 1)\,. \qquad (2)$$

The probability p_k in equation (2) naturally depends on the number of inspection points the planner places on the road network, but it also depends on the trip distance d_k, since the longer the trip the greater the chance of finding an inspection point. The *rationale* behind this is that the planner, faced with a given fixed budget (total number of detectors for the road network), will assign detectors to roads in proportion to road-length; thus, for example, the planner is twice as likely to assign a detector to a 2 km stretch as a 1 km one, since the planner wants to minimise damage, which is linearly related to length.

Assuming a road network to be monitored for overloading that covers N kilometres in total and having w inspection points uniformly distributed across this network, the probability r of being detected on any one randomly-selected kilometre is $r = \frac{w}{N}$. Hence, the probability of *evading* detection in one kilometre is $1 - r$, whilst the probability of evading detection along a full trip of d kilometres is $(1 - r)^d$, assuming independence between kilometre sections. So, the probability p of being detected in a d kilometre trip is:

$$p = 1 - (1 - r)^d \;. \qquad (3)$$

Substituting this expression (3) into equation (2) gives:

$$C_{1k} = T_k\left[\left(V_k(x_k) + \frac{E_k}{x_k L_k}\right)d_k + \left(\frac{x_k - 1}{x_k}\right)\left(1 - \left(1 - \frac{w}{N}\right)^{d_k}\right)F\right] \qquad (x_k \geq 1) \qquad (4)$$

Given the values of the fine level F and number of inspection points w determined by the planner, it is assumed that a class k carrier will search for the optimal load factor x_k^* minimising C_{1k} in equation (4), even if this causes the carrier to overload. For this optimising purpose this equation shows that the total tonnes T_k to move is not relevant, and the impact of fines on the carrier's cost C_{1k} vanishes when the load factor $x_k = 1$.

3.3 Upper level objective: The road planner's objective

The road repair costs result from the damage that lorries inflict on the road according to the load factor at which carriers choose to operate. For each class *k*, the damaging power is evaluated from the unit damage cost *U* (in monetary units per ESAL-km) and a function $g_k(x_k)$ estimating the resulting ESALs from the vehicle load factor x_k. In this context, it should be recalled that the class *k* might reflect the vehicle type as well as the assumed distribution of the load and the suspension type for the lorry (though in the case-study reported in section 5, we shall take *k* to represent only vehicle type).

To control overloading, the planner must choose the number of inspection points *w* on the road and the imposition of a fine *F* in monetary units per tonne in excess of the legal limit. On the fine level *F*, it would seem sensible to impose an upper bound on the permissible values, since otherwise it may have negative economic impacts on the ability to trade and move goods. While the manning of inspection points has a cost for the planner, the resulting fine collection is an income that reduces total costs. So the expected cost to the planner is:

$C_2 =$ road damage cost – total expected fines + cost of manning inspection points.

As previously in section 3.2, we consider a road network of a total length of *N* kilometres with *w* inspection points, and denote:

U = unit damage cost per ESAL-km

$g_k(x_k)$ = ESALs function for class *k*, dependent on load factor x_k

S = cost of manning one inspection point.

As in section 3.2, the number of vehicles required to move T_k tonnes a distance of d_k kilometres is $\dfrac{T_k}{x_k L_k}$. Then, for each vehicle of class *k* the road damage cost imposed is $Ud_k g_k(x_k)$ and the expected fine for the excess tonnes is $(x_k - 1)L_k\left(1-\left(1-\dfrac{w}{N}\right)^{d_k}\right)F$, giving the total expected cost for the planner as:

$$C_2 = \left\{\sum_{k=1}^{K}\frac{T_k}{x_k L_k}\left[Ud_k g_k(x) - (x_k - 1)L_k\left(1-\left(1-\frac{w}{N}\right)^{d_k}\right)F\right]\right\} + Sw \qquad (x_k \geq 1, \forall k) \quad (5)$$

which simplifies to:

$$C_2 = \left\{ \sum_{k=1}^{K} T_k \left[\frac{Ud_k g_k(x_k)}{x_k L_k} - \left(\frac{x_k - 1}{x_k} \right) \left(1 - \left(1 - \frac{w}{N} \right)^{d_k} \right) F \right] \right\} + Sw \qquad (x_k \geq 1, \forall k). \qquad (6)$$

3.4 The bi-level carrier/planner interaction problem

Once the mutual influence of carriers' and planners' decisions is recognised, the planner's proactive character and his/her implicit authority to regulate road transport entitle this actor to play the leading part in this interaction. The planner, conceived in this proactive role, is assumed to know the possible reactions of carriers under diverse circumstances and thereby may anticipate them. The road planner may thus select some of his/her decision variables to induce the carriers' behaviour in the direction of meeting the planner's objectives.

We should stress at this point that the purpose of our approach is to find a kind of 'behavioural equilibrium', a stable point where the individual actors (planner and carriers) have no incentive to change their behaviour based on their individual objectives. This is very different from a global system-optimum where the costs and benefits to all actors appear in a single, weighted objective function, but where the solution may not be realisable or may be unstable.

In terms of the cost objective functions for the carrier and the planner described in equations (4) and (6) respectively, the bi-level optimisation problem to solve is:

$$\text{Minimise} \quad C_2 = \sum_{k=1}^{K} T_k \left[\frac{Ud_k g_k(x_k)}{x_k L_k} - \left(\frac{x_k - 1}{x_k} \right) \left(1 - \left(1 - \frac{w}{N} \right)^{d_k} \right) F \right] + Sw \quad \text{with respect to} (F, w)$$

subject to the constraint that for $k = 1,2,...,K$, each x_k solves:

$$\text{Minimise} \quad C_{1k} = T_k \left[\left(V_k(x_k) + \frac{E_k}{x_k L_k} \right) d_k + \left(\frac{x_k - 1}{x_k} \right) \left(1 - \left(1 - \frac{w}{N} \right)^{d_k} \right) F \right] \quad \text{with respect to} \, x_k$$

where:

$$1 \leq x_k \leq x_M \ (k = 1,2,...K); \quad 0 \leq F \leq F_M \ ; \quad w \in \{1,2,...,w_M\} \qquad (7)$$

where it is assumed that x_M is the maximal load factor that physically a lorry can stand (say, $x_M = 3$ may be a reasonable assumption), F_M is the maximum politically acceptable fine level and w_M is the maximal number of inspection points the planner is able to install.

It should be noted that this approach differs from the equilibrium resulting from a procedure whereby the planner starts by making a decision, then the carrier responds with his/her own decision, then the planner makes a subsequent move and so on, as would happen in a Nash non-cooperative game (see for example: Fisk, 1984). The approach presented, rather than searching for a non-cooperative equilibrium under a series of planner-carrier decisions, develops the optimal solution instead by moving on the surface constraints that define the optimal decisions for the carrier under the choice possibilities of the planner. That is to say, there is a hierarchy in the decision-making. In this way, the road planner, able to predict any reaction of the carrier, will choose the most appropriate combination of number of inspection points and fine levels so as to get the minimal total expenditure (on repair and overloading inspection costs, less fine revenue).

Our purpose in constructing problem (7) is to define the potentially conflicting processes of planner and carrier, and with this in mind our way of applying this approach in the following two sections will be to explore and plot the objective function surfaces numerically. Our purpose in exploring the surfaces can be distinguished from an aim to devise efficient methods for computing bi-level optimum solutions. For the reader who may be interested in such algorithmic approaches, see, for example, Yang & Bell (2001), where congestion leads to interdependencies in the travel choices, and where the resulting problem has the much more complex nature of an MPEC, Mathematical Program with Equilibrium Constraints (Luo, Pang and Ralph, 1996).

4. CASE STUDY: OVERLOADING EVIDENCE FROM MEXICO

In 1991 the Mexican Secretariat of Communications and Transport (SCT) began conducting an annual road freight survey to collect data on lorries intercepted whilst using the paved road network. The main objective of this field study was to improve the knowledge of lorry traffic, since the usual sources arising from invoices, permits and taxes could not give information about local traffic, seasonal variations in flows, or overloading (Rico *et al*, 1997). The annual survey identifies the type of vehicle used, the size and weight of the vehicle sampled, the type of cargo moved, the origin and destination of movement, the kind of packing used, and the type of trade for the load (domestic or international). Information on overloading has emerged from these surveys, allowing a first look at the problem in Mexico based on actual data. From these surveys the five main vehicle types, representing nearly 97% of the fleet surveyed, were identified: rigid 2-axles, rigid 3-axles, articulated 5-axles, articulated 6-axles and double articulated 9-axles. The Mexican classification code for these vehicle types is: C2, C3, T3S2, T3S3 and T3S2R4, respectively.

The infringement to GVW limits can be seen from the average GVWs recorded in the surveys. Table 3 displays the average GVW recorded in the surveys from 1995 to 1997 along with the resulting load factor for each vehicle type. This table shows average load factors approximately between 1.2 and 1.3, for all vehicle types, as well as the higher tonnes in excess carried by the articulated lorry types, as compared to those moved by the rigid types.

Vehicle type	Maximum Legal GVW (tonnes)	Maximum Payload (tonnes)	1995			1996			1997		
			Average GVW (tonnes)	Excess tonnes	Load factor	Average GVW (tonnes)	Excess tonnes	Load factor	Average GVW (tonnes)	Excess tonnes	Load factor
C2	17.5	9.8	19.5	2.0	1.20	20.3	2.8	1.29	19.8	2.3	1.23
C3	26	17.3	29.6	3.6	1.21	30.8	4.8	1.28	30.2	4.2	1.24
T3-S2	44	25	50.4	6.4	1.26	50.4	6.4	1.26	50.3	6.3	1.25
T3-S3	48.5	35.1	58	9.5	1.27	57.3	8.8	1.25	58.7	10.2	1.29
T3-S2-R4	66.5	48	82.6	16.1	1.34	81.2	14.7	1.31	80.8	14.3	1.30

Table 3: GVWs in overloaded Mexican lorries. (based on Gutiérrez & Mendoza, 2000)

Figure 1 shows GVW averages, as well as the maximum permitted GVW in 1996, for three trip conditions: empty movement; not overloaded; and overloaded.

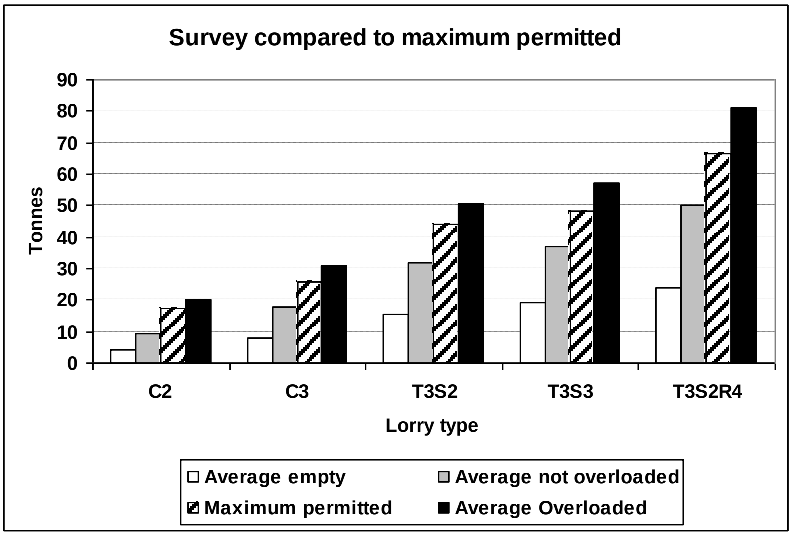

Figure 1: Average GVW for Mexican lorries in the 1996 survey (based on Gutiérrez *et al*, 1999).

The degree of overloading for individual axles was also detected in these surveys. Table 4 displays the ratios of average weights on axles to maximum permitted axle weight of the five Mexican lorry types, with data of 92113 vehicles recorded in 15 survey stations (Rascón *et al*, 1997). Particularly noteworthy in these data are the remarkable average excesses of 16% and 43% for tractive double axle 2+3 and triple axle 4+5+6 in the articulated type T3S3, respectively.

Type	Axle1	Axle2	Axle 2+3	Axle 4+5	Axle 6+7	Axle 8+9	Axle 4+5+6
C2	0.51	0.72					
C3	0.66		0.95				
T3S2	0.63		0.80	0.88			
T3S3	0.64		1.16				1.43
T3S2R4	0.66		0.89	1.02	0.80	0.96	

Table 4: Ratio of observed average axle weight of loaded lorries to permitted maximum axle weight: Five main Mexican types (based on Rascón *et al*, 1997)

Table 5 shows the percentage of axles exceeding the maximum permitted axle load recorded in the 1996 survey. This table indicates that tractive double axle 2+3, both in the rigid C3 type and in all the articulated types, represents the most common violation to axle load limits, whereas steering axle 1 represents the least common violation. This reflects variable load distribution along the lorry platform, which has almost no effect on axle 1, as compared to the rest of the axle groups. As background to these data, it should be noted that they occur in spite of weight enforcement, which is in place for lorries overloading both in GVW and in axle loads. Apart from vehicle detention and permit revocation for recidivists, violators face fines increasing with the degree of excess load.

	Single axle		Double Axle				Triple Axle
Vehicle type	1	2	2+3	4+5	6+7	8+9	4+5+6
C2	0.3	6.1	---	---	---	---	---
C3	2.9	---	33.0	---	---	---	---
T3S2	0.2	---	36.9	24.8	---	---	---
T3S3	1.3	---	49.0	---	---	---	34.5
T3S2R4	0.1	---	42.6	29.1	11.2	23.5	---

Table 5: Percentages of axles exceeding axle load limits for loaded Mexican lorries in 1996 (Gutiérrez et al, 1999)

5. APPLICATION OF BI-LEVEL APPROACH TO MEXICO CASE STUDY

5.1 Context

In order to provide a clear example of the way in which our bi-level modelling approach could be applied, we shall consider a particular context for our Mexico case study network. We suppose that there is a given total amount of some bulk commodity that needs to be moved over a portion of the road network; we assume that lorries are not currently carrying dense goods and so are not overloaded, thus the network currently has no inspection points for overloading control. We shall apply our method to the five lorry types introduced in section 4, assuming that market forces will lead all carriers to choose to run just a one of these lorry types for this bulk commodity.

5.2 Estimating ESALs and VOCs

In order to apply the modelling approach presented in problem (7) to the Mexico case study described in section 4, we must first estimate the functions $g_k(x_k)$ (measuring the ESALs imposed on the road by each vehicle class *k*) and $V_k(x_k)$ (measuring the operating cost per Tkm for vehicle class *k*). In this particular study, five classes were used corresponding to five different vehicle types, and so we will use the terms ‘class’ and ‘vehicle type’ interchangeably.

Focusing first on $g_k(x_k)$, a function was estimated from ESAL calculations based on the axle weights observed in each type of vehicle surveyed in 1997. In that year, twenty survey stations weighed 128,619 vehicles, giving values for the average weight for individual axles in each lorry type. With these average weights of axles, the corresponding load factor and ESALs were estimated. By comparing the model fit of various functional forms to these data, the *g* functions illustrated in Figure 2 were selected. These particular *g* functions are based on a fourth order polynomial, for which the individual coefficients are of no interest as they are subject to multi-collinearity, a problem which does not affect predictions (which is the sole purpose we have for using these functions). From Figure 6, the vehicles can be ordered in decreasing order of sensitivity of ESALs to the load factor, as: T3S2, T3S3, C3, T3S2R4 and C2. This suggests that for enforcement purposes, the most controlled vehicle type should be T3S2, followed by T3S3 and C3.

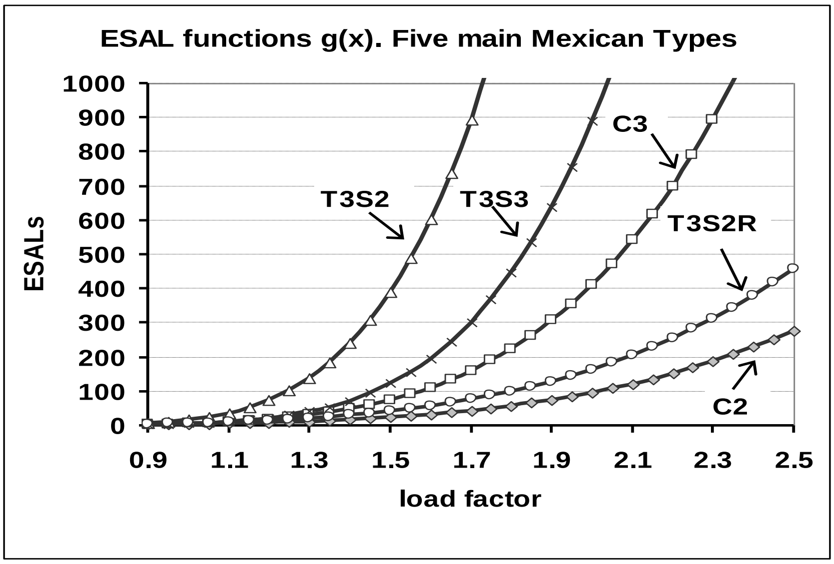

Figure 2: ESAL functions for the five main Mexican vehicle types

Moving on to the estimation of the vehicle operating costs (VOC), these were obtained through several runs of the World Bank’s HDM-VOC v.4.0 software, which calculates the physical consumption and vehicle operating costs for a range of vehicle types and a range of road characteristics. This model stems from a major World Bank programme: the Highway Design and Maintenance (HDM) Standards Study. Several experiments and user-surveys (conducted in Kenya, Brazil, India and the Caribbean) generated a vast amount of knowledge on vehicle operating costs under a diversity of road conditions, and much of this is adapted in the model to the user’s conditions (Archondo-Callao. and Faiz, 1994, pp. 6-10).

Based on the lorries’ unit costs from 2001 reported in a Mexican study (Arroyo and Aguerrebere, 2002), the HDM-VOC v.4.0 was run assuming that all vehicles moved in a free-flowing traffic environment, on a homogeneous road pavement of fair quality, with a moderate roughness (International Roughness Index, IRI = 2.5 m/km), an average gradient of 3%, and horizontal curvature of 100°/km. This is typical of the road type that one may encounter in Mexico. Figure 3 shows the VOC per Tonne-km obtained for the main five Mexican types. Appendix 1 shows the input data used in these runs for the Mexican type rigid 3-axles (code classified “C3”). “Cargo Delay Cost” was estimated based on Values of Time (VOT) for Mexican lorries in 1992 reported by the World Bank (Gwilliam, 1997), and adjusted to prices in 2001. Crew time costs were obtained from Arroyo and Aguerrebere (2002).

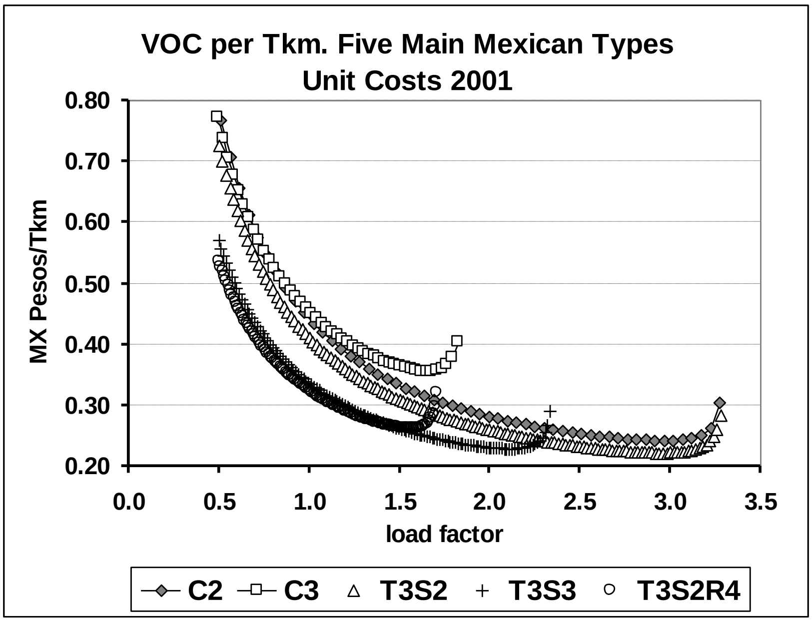

Figure 3: VOC per Tonne-km. Five main Mexican types (using the results presented in Table 6)

Based on these observations, VOC per Tkm functions $V_k(x)$ were fitted for each vehicle type. The general fitting equation used was:

$$V(x) = \frac{\theta}{x} + \beta_0 + \beta_1 x + \beta_2 x^2 \quad . \tag{8}$$

The term $\frac{\theta}{x}$ in equation (8) reflects the reduction of average costs as fewer vehicles are required to move a given tonnage, whilst the quadratic term $\beta_0 + \beta_1 x + \beta_2 x^2$ reflects the increasing driving time and maintenance costs as load factors rise to the point at which the vehicle becomes unable to move (and the function becomes vertical). Table 6 displays the results of the statistical fitting exercise and Table 7 gives the results in equation form. These functions are illustrated in Figure 3, and as can be seen the minima occur at different load factors for different lorry types.

Vehicle Type	Coefficients				R-sq
	θ	β_0	β_1	β_2	
C2	**0.311** **(24.114)**	**0.182** **(5.956)**	**-0.067** **(-3.261)**	**0.018** **(4.587)**	**0.996**
C3	**0.226** **(10.356)**	**0.456** **(6.524)**	**-0.371** **(-5.391)**	**0.141** **(6.694)**	**0.997**
T3S2	**0.284** **(44.467)**	**0.180** **(11.944)**	**-0.068** **(-6.754)**	**0.018** **(8.932)**	**0.997**
T3S3	**0.183** **(19.776)**	**0.264** **(10.176)**	**-0.161** **(-7.424)**	**0.051** **(9.164)**	**0.995**
T3S2R4	**0.118** **(7.569)**	**0.458** **(9.002)**	**-0.407** **(-7.870)**	**0.152** **(9.230)**	**0.994**

Table 6: Estimated coefficients and t-values for VOC/Tkm functions

Type	Fitted equation
C2	$V_1(x) = \dfrac{0.311}{x} + 0.182 - 0.067x + 0.019x^2$
C3	$V_2(x) = \dfrac{0.226}{x} + 0.456 - 0.371x + 0.141x^2$
T3S2	$V_3(x) = \dfrac{0.284}{x} + 0.180 - 0.068x + 0.018x^2$
T3S3	$V_4(x) = \dfrac{0.183}{x} + 0.264 - 0.161x + 0.051x^2$
T3S2R4	$V_5(x) = \dfrac{0.118}{x} + 0.458 - 0.407x + 0.152x^2$

Table 7: Fitted equations for VOC/Tkm functions

5.3 Solution Procedure

Our procedure for analysing optimisation problem (7) basically consists of constructing a picture of the complete upper-level surface over which the planner may search, when ‘constrained’ (mathematically) by the load-factor decisions that globally minimise the lower level problem at some given levels of enforcement. We shall then observe and interpret features of this surface. In order to do this we evaluate the upper level objective function C_2 at each of a grid of values for the number of weighing stations w and fine level F, when each load factor x_k in C_2 is given by the global minimiser $x_k^*(w,F)$ of the lower level objective C_{1k} with respect to x_k, at those values of *w* and *F*. An alternative approach would have been to utilise an optimisation algorithm to find local stationary points of the mixed-integer bi-level problem (7). Our approach, though less elegant, has the advantage that we are able to explore features of the surfaces of both planner and carriers, including the possibility for the existence of multiple stationary solutions, and to examine the trade-off between enforcement levels and maintenance costs for sub-optimal solutions.

5.4 Results and Policy Implications

In our model, the planner's ability to make a positive influence is highly determined by the responses induced in the carriers, and so it is a natural first step to understand the nature of this response (i.e. "the lower level problem" of (7)). Figures 4 and 5 illustrate the optimal load factor $x_k^*(w,F)$ over a region of values for (*w*, *F*), for the Mexican lorry types C3 and T3S3. In both cases, the assumed trip has a length of 850 km and must move 600 tonnes in total.

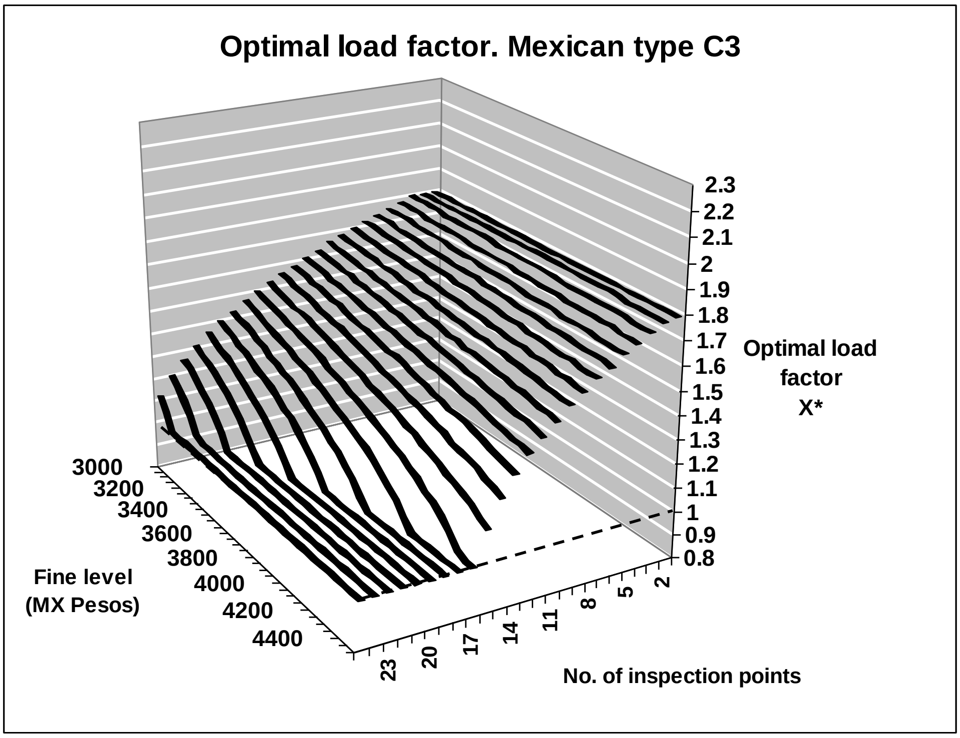

Figure 4. Carriers' optimal load factor for Mexican type C3, as a function of the number of inspection points and the fine level.

The VOC per Tkm functions used are those calculated in Table 7. The fine level range considered is $3000 \le F \le 4500$ (Mexican Pesos) in steps of 50, and the number of weighing stations considered is $w \in \{1,2,...,25\}$. The network length assumed was 110,000 km, approximately the length of the current Mexican paved road network. Figures 4 and 5 exhibit the deterrent effect of increasing fines and the number of weigh-stations on the optimal load factor for the carriers.

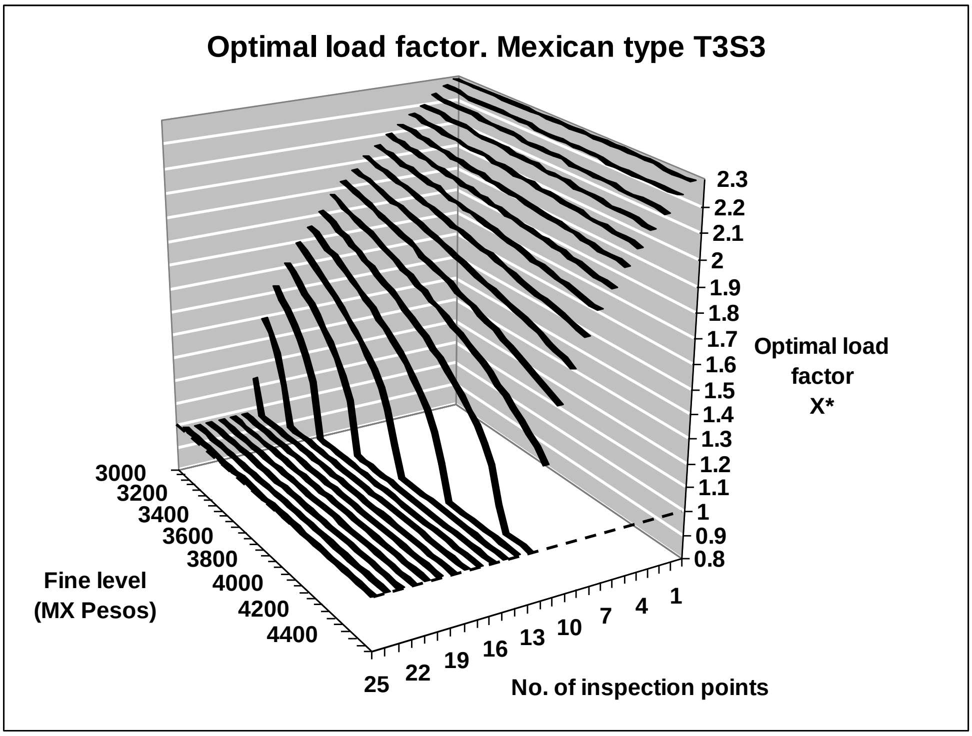

Figure 5. Carriers' optimal load factor for Mexican type T3S3, as a function of the number of inspection points and the fine level.

Both Figures 4 and 5 show that as more weighing stations are installed and higher levels of fine are set, the surfaces ultimately flatten so that the carrier chooses an optimal load factor as $x^* = 1$, i.e. exactly the legal payload (where, it should be recalled, we assume that the cargo is dense enough for us to neglect volume constraints). On the other hand, there exist many plausible combinations of fine level and number of weigh stations at which overloading is an optimal decision to make for the planner, in spite of the fine; thus we are able to capture the realistic phenomenon of overloading observed in the surveys reported in section 4.

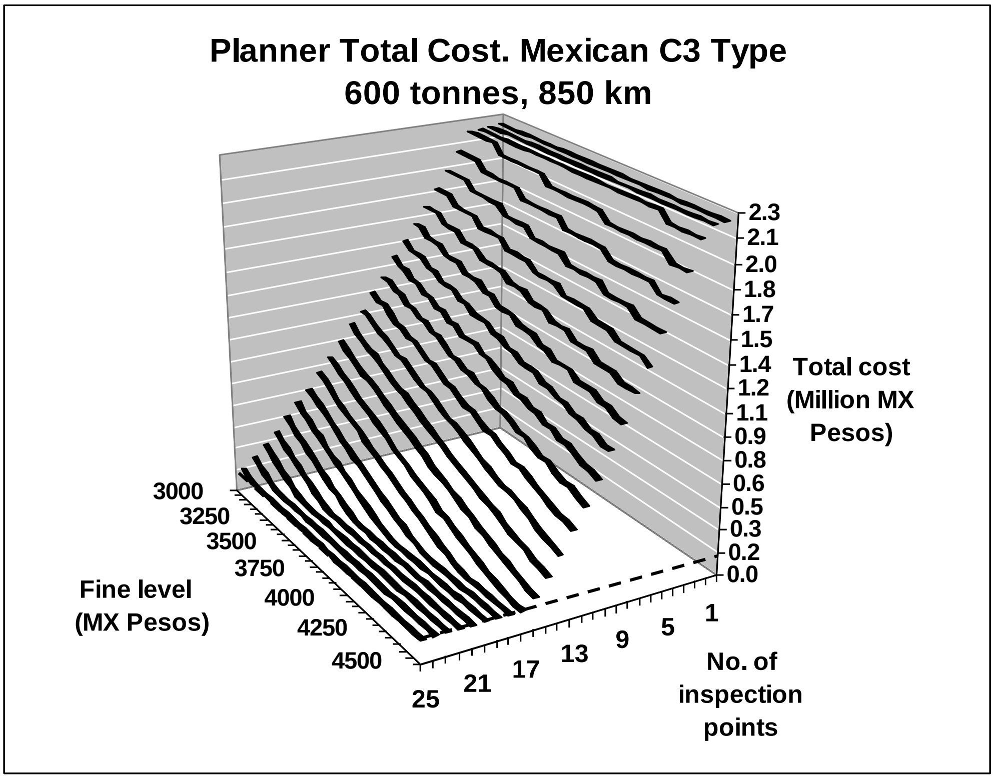

Figure 6. Total planner's cost as a function of the number of inspection points and fine level, anticipating response of carriers. Mexican Type C3 traffic example.

Let us now consider what happens when these responses of the carriers are embedded in the planner's upper level objective function. Figures 6 and 7 show the resulting surfaces for the planner when there is a single lorry/carrier type responding (i.e. $K = 1$); in Figure 6, the single type is the Mexican types C3, and in Figure 7 it is type T3S3, and so Figures 6 and 7 are a counterpart to Figures 4 and 5. These Figures show that we are able to capture the plausible, decreasing trend of the planner's total cost as more inspection points are set and fine levels are increased, even when we take account of enforcement costs. Following the carrier's responses, shown in previous Figures 4 and 5, the planner's total cost surfaces flatten once the optimal load factor falls to unity, with just a small upward tilt as extra inspection points are added.

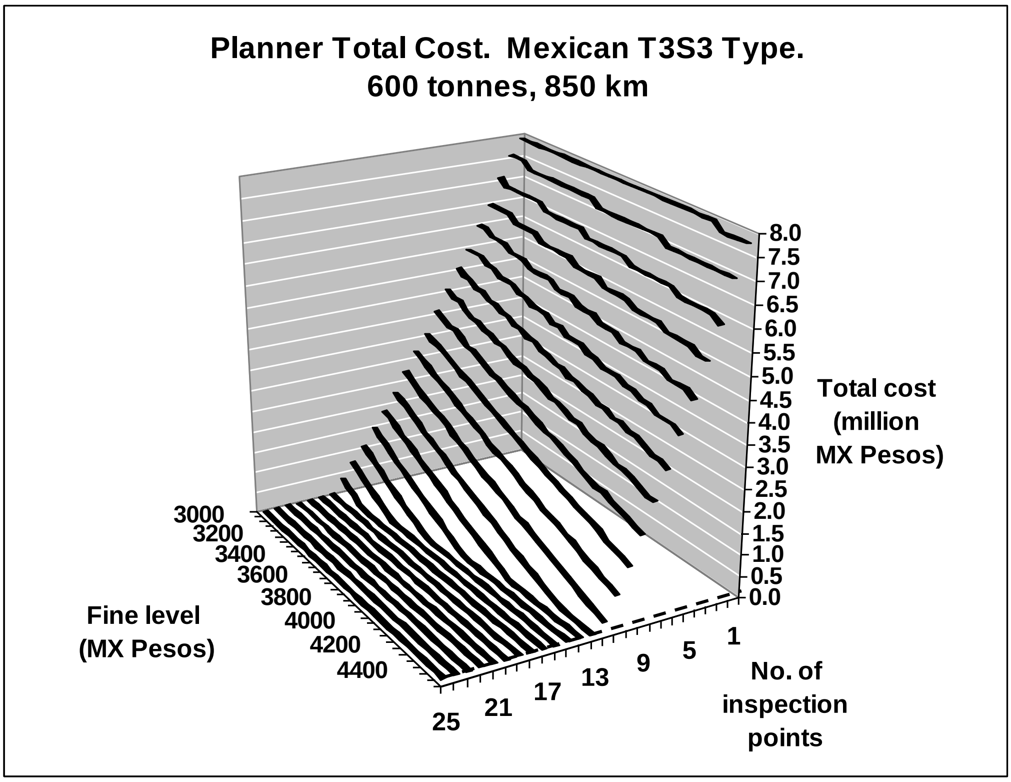

Figure7. Total planner's cost as a function of the number of inspection points and fine level, anticipating response of carriers. Mexican Type T3S3 traffic example.

This procedure was repeated for the five main Mexican types, assuming the same conditions of total tonnage and distance covered, and in each case assuming that all vehicles are of that single type. These results are shown in Tables 8 and 9.

Type	Optimal Fine Level	Optimal No. of inspection points	Estimated Minimal Planner's Cost	Road damage cost	Fine Income	Inspection Cost	Carrier's Optimal Load Factor chosen
C2	≥4330	19	122184	112684	0	9500	1.00
C3	≥4420	17	116508	108008	0	8500	1.00
T3S2	≥4440	17	212907	204407	0	8500	1.00
T3S3	≥4310	13	64894	58394	0	6500	1.00
T3S2R4	4400	11	43227	59051	21323	5500	1.11

Table 8. Planner's cost components at optimal solutions to the bi-level problem

Type	Optimal Fine Level	Optimal No. of inspection points	Estimated Carrier's Cost	No. of lorries used	Vehicle operating cost	Empty run cost	Fine cost	Carrier's Optimal Load Factor chosen
C2	≥4330	19	407188	61.4	226950	180239	0	1.00
C3	≥4420	17	396019	34.7	230520	165499	0	1.00
T3S2	≥4440	17	376007	24.0	211140	164867	0	1.00
T3S3	≥4310	13	294969	17.1	171870	123099	0	1.00
T3S2R4	4400	11	274064	11.3	152906	99835	21323	1.11

Table 9. Carrier's cost components at optimal solutions to the bi-level problem

Tables 8 and 9 are inter-linked, and so need to be carefully explained. We shall begin by focusing on just one row of each table, corresponding to vehicle type C3. Tables 8 and 9 indicate that (for this type C3) there is a region of optimal solutions to the bi-level problem, these optimal solutions occurring when (i) the number of inspection points is 17, and the fine level is at least 4420, and (ii) the carrier's LF (Load Factor) is 1.00. Since at such a solution no fines are being paid, then raising the fine level above 4420 adds no income to the planner and no cost to the carrier. On the other hand, at a fine level of at least 4420, increasing the number of inspection points beyond 17 would add cost for the planner, but would gain no reduction in damage cost because there is no overloading to deter, and therefore strategies involving more than 17 points could not be optimal. Turning attention to Table 9, again just focusing on vehicle type C3, then we can see the total carrier's cost at the bi-level solutions, as well as the components of this cost (vehicle operating cost, empty running cost and fine cost). For this vehicle type, the policy implication is that the fine level and number of inspection points gives a sufficient deterrent to any overloading, and thus the fine cost is zero; however, this does not mean that the values of the fine level and number of inspection points are immaterial, since they are active in controlling the load factor.

Turning our attention to an alternative vehicle type, namely T3S2R4, we see a rather different kind of solution, and thereby different policy implications. In this case there is a unique solution to the bi-level problem (subject to the rounding used in the discretisation of fine levels). Looking at Table 9, it is noticeable that this vehicle type requires significantly fewer lorries than other vehicle types; this is because this is a larger vehicle with a greater capacity, and because at the optimal solution the carriers are choosing to overload it (by 11%). In doing so, the carriers are choosing to accept a fine cost of 21323; if they chose not to overload, then they would incur a greater cost (in terms of operating and empty running cost) in needing more vehicles. However, it is important to appreciate when comparing the carrier's response for T3S2R4 with that for C3, we are not comparing their response at the same fine/inspection levels; it is the decisions of the *planner* that are effectively driving the differing decisions of the carrier regarding overloading. Looking now at Table 8, we see for type T3S2R4 the same figure 21323 as income to the planner, which is sufficient to outweigh the road damage cost caused by the overloading. This solution is globally stable in the sense that neither carrier nor planner has any incentive to move from the solution shown, and there are incentives for any deviation from this solution to be reversed. Having chosen type T3S2R4, carriers have no incentive to choose a load factor of other than 1.11, and the planner has no incentive to change from having 11 inspection points (with continually changing locations) and a fine level of 4400. Should the carriers acquire any other type of lorry, the planner will increase the number of inspection points (as per Table 8) and carriers will find themselves with higher costs than if using type T3S2R4, even with the additional inspection points (not shown), and market forces will dictate a change to using type T3S2R4. This example illustrates the benefits of our approach, in being able to suggest an optimal policy for the planner while handling the complexity of these interactions between the different decision-makers.

A final interesting implication of this case study may be seen by comparing all five lorry types in Tables 8 and 9. From these tables, the lorry type giving the smallest optimal planner cost is 43227 for type T3S2R4, and in fact in this example this type also gives the smallest optimal carrier cost (of 274064). Therefore, if the carrier has the choice of which type of lorry to operate, which is what we would expect in the long run, then it is optimal for *both* the planner and carrier for this load to be transported by vehicles of type T3S2R4. It should be noted that the fact that planner and carrier objectives would pull in the same direction is not a necessary condition (in contrast with system optimization methods, for example; Crainic *et al*, 1990), but rather is an *outcome* of applying our method to this case-study.

6. CONCLUDING REMARKS

This paper has extended the methods for modelling multi-actor, multi-level modelling approaches in freight transport (Nagurney *et al*, 2002; Nagurney & Toyasaki, 2005)—which consider manufacturers, retailers and consumers as decision-makers—to take into account the objective of a *planner* who aims for a societal optimum by minimising expenditure on road maintenance costs though overloading control. The main contributions of this paper to the literature are as follows:

- A novel modelling approach has been developed in order to explicitly represent the decision-making process of the *planner* aiming for a societal optimum through a **hierarchical, bi-level approach**. This approach explicitly separates the objectives of planners and carriers, representing the anticipatory power of the planning authority as a ‘leader’. This may be contrasted with previous methodological approaches to problems of a similar structure in freight transport, which are limited by the fact that they aim to incorporate conflicting objectives of the actors into a *single level* optimization problem, either by constraints (e.g. Hu *et al*, 2002; Nozick, 2001; Jula *et al*, 2005), weighted optimization (e.g. Korpela *et al*, 2001), or a (single-level) multi-objective optimization (Tzeng *et al*, 2007).
- As a component of our modelling approach, we have **developed functions to represent the objectives of planners and carriers** and have related these to decisions each may selfishly make. This provides a more realistic alternative to the aggregate ‘system-optimal’ methods (e.g. Crainic *et al*, 1990) of strategic freight transport planning, which aim to compute the *potential* benefits that would be theoretically attainable if all players conformed to the wishes of a central authority. Our bi-level method, in contrast, assumes that each player will act in their own best interest. As a result, our method produces an attainable optimum solution, rather than a theoretical optimum, as well as providing the policy measures that would lead to such an attainable optimum.
- We have demonstrated our approach with **a case study of Mexico**, with procedures described for calibrating the elements of our method, exploiting a variety of data sources on loading practices and road damage effects. The results of the case study are a contribution to the public policy literature on road planning and maintenance (Dueker & Fischer, 2003; McKinnon, 2005; Babcock & Sanderson, 2006; Knight *et al*, 2008).

We believe that, in the future, the method proposed is easily generalisable, either with alternative model assumptions or applied to alternative planning contexts. For example, in terms of the specific model assumptions we have adopted, we may wish to model the impacts of variance in demand caused by variation about the (mean) long-run equilibrium value, or the feedback from an increase in carriers’ costs to the quantity to be shipped (i.e. elastic demand). In terms of alternative planning contexts, the general approach might be applied to other kinds of externality. For example, building on Sathaye *et al* (2010), we might consider extending our method to investigate optimal load factors considering the potentially conflicting objectives of minimising road maintenance impacts and minimising emissions. In this respect, the particular set of assumptions we have addressed in the present paper should be viewed as just one example of a variety of alternative (arguably more realistic) sets of assumptions that could have been made in place of those we chose. It is our intention to take the literature forward, rather than dissuade others from trying other variants in future. Indeed, we feel that these very possibilities, of taking what we have done further, are a large part of the value of the paper.

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Appendix 1. Input Data for Mexican Type in the HDM-VOC v.4.0

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                     FREE-FLOW VEHICLE OPERATING COSTS MODEL

__ Input Data Report ___________________________________________________________

Roadway Characteristics
  Surface type                  Code: 1-Paved   0-Unpaved                    1
  Average roughness (IRI)                 m/km                            2.50
  Average positive gradient               %                               3.00
  Average negative gradient               %                               3.00
  Proportion of uphill travel             %                              50.00
  Average horizontal curvature            deg/km                        100.00
  Average superelevation                  fraction                        0.01
  Altitude of terrain                     m                            1000.00
  Effective number of lanes     Code:1-One  0-More than one                  0

Heavy truck (Mexican Type C3)

Vehicle Characteristics
  Tare weight                             kg                           8800.00
  Load carried                            kg                              0.00
  Maximum used driving power              metric HP                     190.10
  Maximum used braking power              metric HP                     347.23
  Desired speed                           km/hour                        90.00
  Aerodynamic drag coefficient            dimensionless                   0.85
  Projected frontal area                  m^2                             7.00
  Calibrated engine speed                 rpm                          2100.00
  Energy-efficiency factor                dimensionless                   0.80
  Fuel adjustment factor                  dimensionless                   1.15

Tire Wear Data
  Number of tires per vehicle             #                              10.00
  Wearable volume of rubber per tire      dm^3                            7.30
  Retreading cost per new tire cost       fraction                        0.45
  Maximum number of recaps                dimensionless                   3.39
  Constant term of tread wear model       dm^3/m                          0.16
  Wear coefficient of tread wear model    10E-3 dm^3/kj                  12.78

Vehicle Utilization Data
  Average annual utilization              km                         150000.00
  Average annual utilization              hours                        2860.00
  Hourly utilization ratio                fraction                        0.85
  Average service life                    years                           8.00
  Use constant service life ?   Code: 1-Yes       0-No                       1
  Age of vehicle in kilometers            km                         500000.00
  Passengers per vehicle                  #                               0.00

Unit Costs (Mexican Pesos 2001, based on Arroyo & Aguerrebere, 2002)
  New vehicle price                       $                          508300.00
  Fuel cost                               $/liter                         3.79
  Lubricants cost                         $/liter                        11.32
  New Tire cost                           $/tire                       1361.70
  Crew time cost                          $/hour                         38.30
  Passenger delay cost                    $/hour                          0.00
  Maintenance labor cost                  $/hour                         31.07
  Cargo delay cost                        $/hour                         73.94
  Annual interest rate                    %                              10.00
  Overhead per vehicle-km                 $                               0.47
```