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Modelling planner–carrier interactions in road freight transport: Optimisation of road maintenance costs via overloading control

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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.

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 and Toyasaki, 2005; Sheu et al., 2005; Figueiredo and Mayerle, 2008) and, more recently, third party logistics service providers (Panayides and 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 and 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,

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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 and 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 and 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 and 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 1958–1960 emerged the theory of road damage from axle weight as an nth–power law, with $n \approx 4$ (Highway Research Board, 1962; Small et al., 1989; Cole and Cebon, 1991; TRB, 2007). The *4th-Power Law* states that structural pavement damage for a given axle is nearly proportional to the 4th 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):

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

where A_j is the jth 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).

Table 1
Road damage impacts of several typical UK vehicles (from Urquhart and Rhodes (1990)).

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	18,792
Full laden	6.1	10.16	–	–	16.3	2.709	96,320
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	30,464
Full laden	5.58	10.16	8.38	8.38	32.5	4.836	171,903