ROAD SAFETY AT REASONABLE COST

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ABSTRACT

This paper describes a model for the optimal allocation of road safety resources which has been developed by New Zealand's Land Transport Safety Authority (LTSA) The model permits expenditure to be allocated between regions, intervention types and road types so that efficiency is maximised It can accommodate resource constraints and other policy goals (such as equity). It relies on the principle that road safety interventions should be carried out until the cost of the marginal unit of intervention on the marginal section of road equals its marginal benefit It is illustrated by applying it to road safety enforcement: police patrol hours are allocated optimally between areas The model can in principle be adapted to other types of road expenditure. Refinements and extensions are suggested

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Introduction

'Reasonable cost'

The Land Transport Safety Authority (LTSA) was set up in 1993 'to undertake activities that promote safety in land transport at reasonable cost' (*Land Transport Act* 1993). This objective obliges the LTSA to develop and implement safety programmes which generate a net safety benefit to the nation. To this end the LTSA is developing a procedure to allocate road safety resources optimally (LTSA 1995). This paper describes the LTSA's work and the resource allocation model that has come out of it.

Context and scope of the LTSA resource allocation model

New Zealand currently spends somewhat over a $1 billion a year on its road network (table 1 and figure 1). Of this, about $160 million/yr is coordinated by the LTSA: $20 million expended by the LTSA mostly on education and publicity, and $140 million expended by the Police on traffic management and road safety enforcement. The rest, consisting entirely of road engineering, is expended by various road authorities.

The LTSA model is intended to apply eventually to most road safety spending. However, the model can be regarded as a specific case of a more generalised model which could be applied to non-safety road spending as well. This paper therefore discusses three increasingly specialised versions of the model.

- A 'generalised model' which applies in principle to all road spending on engineering, enforcement and traffic management, that is, the bulk of all road spending in New Zealand
- A 'road safety model' which applies to spending on road safety engineering, enforcement, and some educational programmes.
- An 'enforcement model' which applies only to road safety enforcement by means of police patrol.

So far only the enforcement model has been empirically estimated and used. However, the other two models are presented in this paper because they help us to understand the nature and potential of the LTSA's work

The only type of road expenditure which cannot in principle be modelled is expenditure which is non-spatial, such as licensing, vehicle standards, and certain education and publicity programmes. In future the models may be adapted to include them, but currently they must be evaluated by other means

The problem

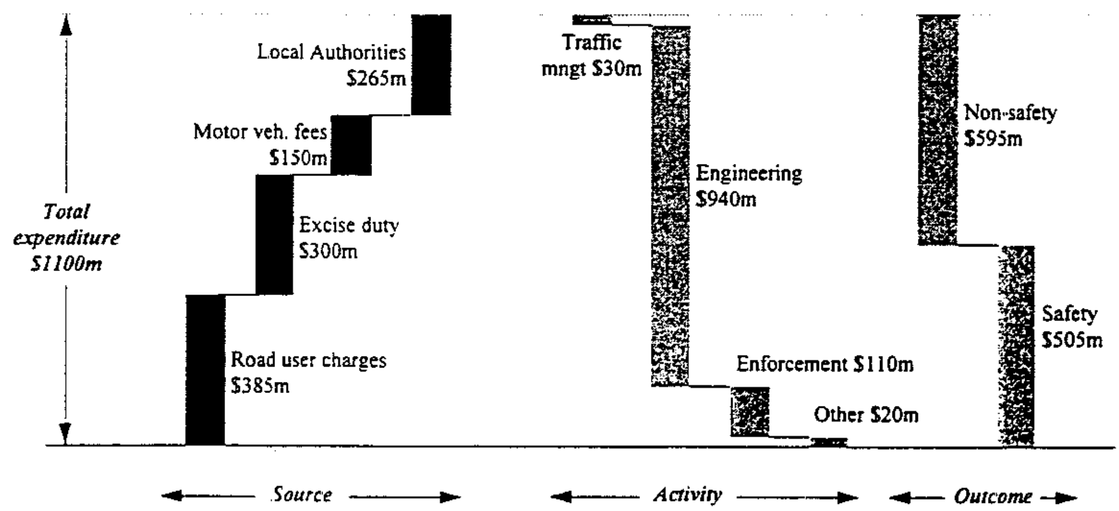
Road agencies (including road safety agencies such as the LTSA) generally allocate resources in three steps. Potential projects are first identified, next evaluated, and finally funded provided certain criteria are satisfied. A 'bottom-up' method of this kind works well if all acceptable projects are identified and the tools exist with which to evaluate them. But this cannot be guaranteed. For instance dangerous locations tend to receive attention only if they have a history of crashes; and some types of spending—enforcement for instance—do not lend themselves to bottom-up evaluation. Moreover any process which examines individual cases on an *ad hoc* basis tends to be susceptible to public pressure, particularly when applied to road safety.

Some road agencies attempt to bypass these difficulties by allocating expenditure to regions on the basis of, say, population or road length. However, simple rules of this kind may achieve equity, but cannot be guaranteed to achieve efficiency.

Table 1 **Road expenditure by agency, activity and outcome: New Zealand 1995 ($ million/yr)**

Agency	Activity	Outcome		
		Safety	*Non-safety*[6]	*Total*
Police	Traffic management[3]		30	*30*
Road authorities	Engineering[1]	375	565	*940*
Police	Enforcement[2]	110		*110*
LTSA	Other[4]	20		*20*
Total[5]		*505*	*595*	*1 100*

Figure 1 **Road expenditure by source, activity and outcome: New Zealand 1995 ($ million/yr)**



Notes (1) Engineering affects the physical road infrastructure, for instance intersection treatments. lighting. signage and changes to road geometry (2) Enforcement affects road-users' compliance with the law, for instance police patrol and speed cameras (3) Traffic management consists of sanctions. investigations, and incident attendance etc (4) 'Other' interventions include licensing. vehicle standards, education and publicity; and excludes $40 million/yr cost of revenue collection by the LTSA. (5) Excludes fuel taxes of approximately $600 million/yr. none of which is allocated to road expenditure (6) Consists of savings in travel time and vehicle operating cost **Source** LTSA

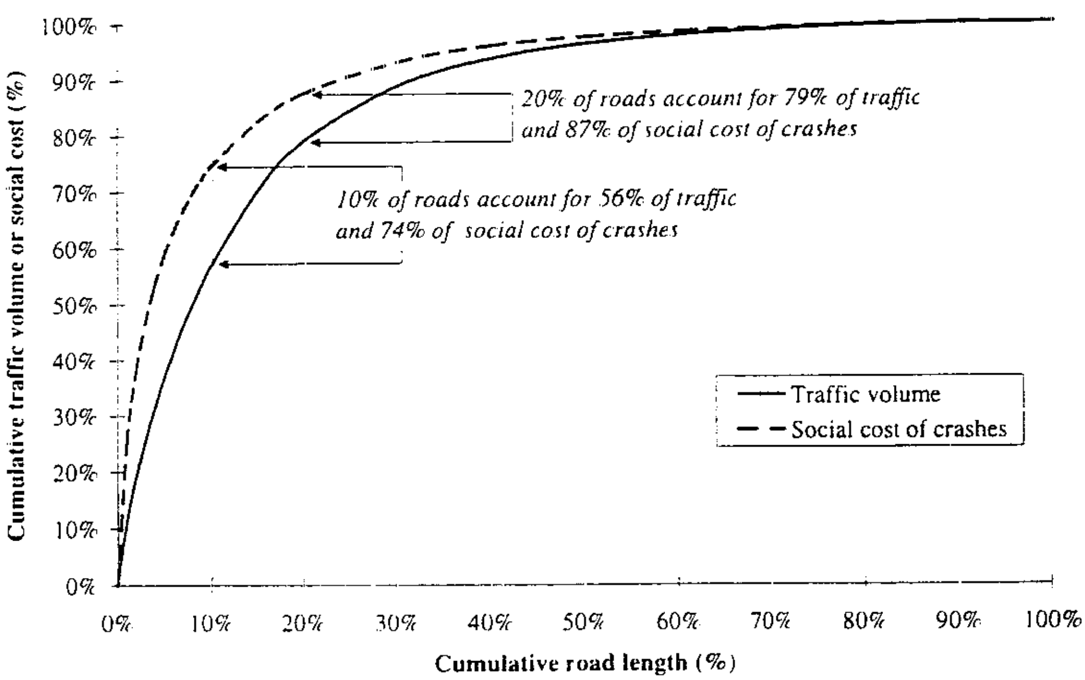
In this paper we show how the LTSA is overcoming these difficulties. Instead of allocating resources to individual projects as they are approved, resources are allocated to regions and types of interventions in such a way as to maximise overall efficiency—a 'top-down' approach. This ensures that resources are allocated optimally even when not all acceptable projects can be identified. However, because the top-down approach does not identify individual projects, conventional bottom-up evaluation may still be used to complement it. At the strategic level the LTSA's approach to road safety has much in common with that of the Dutch, which is embodied in the Netherlands National Road Safety Plan (SWOV 1991, 1992; Wegman et al. 1994).

Approach

The LTSA's approach to the allocation of road safety resources was prompted by the fact that most traffic—and hence most of the social cost of crashes, travel time cost, and vehicle operating cost—is concentrated on a small part of the road network (figure 2). It followed from this that it ought to be possible to capture most of the benefits of road projects by the careful targeting of the network. What was needed was a tool for systematically identifying those parts of the network which offered the best payoff.

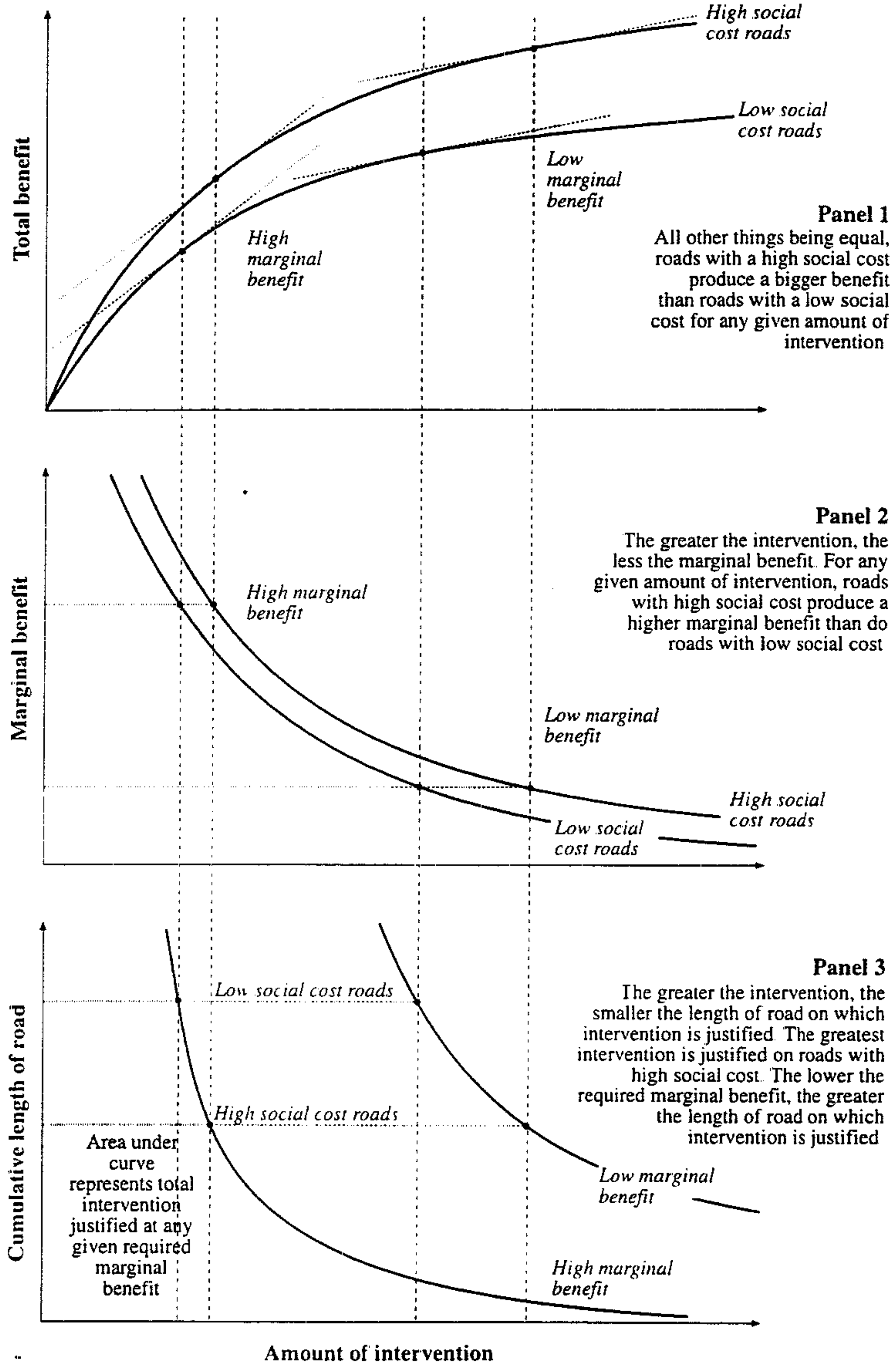
That tool is marginal analysis (figure 3). Marginal analysis is a technique for allocating resources optimally to competing uses: it tells us how much to spend in total (the total budget), and where and how to spend it (resource allocation).

Figure 2 **Traffic volume and social cost of crashes, by road length: New Zealand**



Note Cumulative travel time cost and vehicle operating cost are not shown but resemble the curves for traffic social cost of crashes, which are shown. **Source** LTSA

Figure 3 **Marginal analysis of road safety projects**



Total budget

Marginal analysis tells us that in the absence of constraints (see below) the last—or 'marginal'—unit of an intervention should produce the same amount of benefit as it costs, wherever it is implemented and whatever form it takes. For example, the marginal hour of police patrol should produce a benefit that equals the cost of that hour. If it does not, the amount of intervention should be increased or decreased until it does. In this way we determine the total amount of resources to devote to the intervention.

Resource allocation

Marginal analysis tells us that in the absence of constraints (see below) the marginal dollar spent on any intervention should produce the same benefit wherever and however it is spent. If it does not, it is better to take resources from one place and devote them elsewhere. In this way total benefit is increased for no increase in total cost. The same applies to expenditure on different types of intervention: the marginal dollar of enforcement, say, should have the same benefit as the marginal dollar of engineering. From this we determine how to allocate spending to competing roads and interventions.

Constraints

In practice resource allocation is nearly always constrained—in resources, for reasons of equity, or technically.

- *Resource constraints.* Normally, funds (and sometimes other resources) are limited. Where this happens, it can be shown that it is optimal to set the ratio of marginal benefit to marginal cost to a constant exceeding unity such that all resources are exhausted. This is the optimality condition adopted in this paper.

- *Equity constraints.* It may be judged that certain sections of the population merit a higher level of road safety than might otherwise be allocated to them. Equity constraints can be incorporated mathematically within the model to ensure this happens.

- *Technical constraints.* There is a technical upper limit on the amount of most interventions (a road cannot for instance be patrolled for more than 24 hours a day). Also, many interventions are indivisible: they may be of a binary kind (a road is either edge-marked or not), or may exist in discrete amounts (a road must have one more lane but not half a lane). Where necessary, technical constraints are accommodated mathematically within the model to reflect this.

Generalised model

The general question which every road agency must answer is: *How much of each intervention should be carried out on each part of the road network?* In this section we present a generalised resource allocation model for posing and answering this question. This model can be applied to any road intervention which satisfies two conditions: the interamount of intervention. Since benefit to road users takes the form of a reduction in total social cost of travel (that is, the cost of crashes, travel time and vehicle operation) marginal benefit equals marginal social cost.

The benefit function will generally be estimated from historical data. Separate benefit functions will be needed for each type of intervention. In order to achieve good explanatory power it may also be necessary to partition the data by type of road.

The general form of the benefit function is

$$B_{ij} = f\left(V_i, Q_{ij}, D_i\right) \qquad (1)$$

This states that the benefit B_{ij} of intervention j in spatial unit i depends on (1) the traffic volume V_i, (2) the amount of intervention carried out Q_{ij}, and (3) the size of the spatial unit D_i. For example, the benefit of road safety enforcement in a particular zone depends on traffic volume, the number of patrol-hours carried out, and the length of road in the region. Similarly, the benefit of improved road engineering on a particular road segment depends on traffic volume, the number of (say) intersection improvements carried out, and the length of the road segment.

Why should the benefit depend on these particular variables? It is perhaps obvious why benefit should depend on traffic volume and the amount of intervention; it is less clear why it should depend on the size of the spatial unit. We include this term because the effectiveness of interventions may depend on their spatial concentration—indeed we found this to be so in the case of police patrol. For instance, a given number of police patrol hours—or intersection treatments—is likely to be more effective where traffic is concentrated than where it is diffuse.

Cost function

The cost function is a mathematical relationship between (1) the total cost of resources expended on a given part of the road network, and (2) the amount of intervention carried out on it. Marginal cost is the rate of change of total cost with respect to the amount of intervention. The cost function, unlike the benefit function, will generally be based on direct observation. It may be sufficient to approximate marginal cost to a single parameter: unit cost. Separate cost functions will be required for each type of intervention and, possibly, each type of road.

The general form of the cost function is

$$C_{ij} = g\left(Q_{ij}\right) \qquad (2)$$

This states that the cost C_{ij} of intervention j in spatial unit i depends only on the amount of intervention carried out Q_{ij}. For example, the cost of road safety enforcement in a particular zone depends only on the number of patrol-hours carried out. Similarly, the vention must be spatial (that is, it must be directed at a specific part of the road network and its benefit felt there); and input–output relationships must be quantifiable (that is, from the size, nature and location of the intervention we must be able to predict the benefits that will flow from it).

Spatial unit

The model must be based on a spatial unit whose function is to provide a common 'coinage' in which the model operates: data provided to the model relate to these spatial units, and results from the model relate to the same units.

- *Points.* Some interventions occur at, and their benefits are felt at, discrete points, for instance intersection treatments, bridge treatments, and many other changes in road geometry. For such interventions the ideal spatial unit is the point. For example if we wish to analyse intersection treatments we would ideally use the intersection as our spatial unit.

- *Linear units (road segments).* Many interventions occur along continuous stretches of road; that is, they are imposed over, and their impact felt over, a considerable distance. Examples include certain changes in road geometry and condition, for instance lighting and design speed. For interventions of this kind the road segment is normally the ideal spatial unit as it allows road characteristics and traffic flow—typically recorded at segment level—to be readily incorporated into the model. Ideally road segments should be defined such that each is homogeneous in terms of physical characteristics and traffic volume.

- *Areal units (zones).* Certain interventions—police enforcement is one—exert a 'halo' effect in that they act over a wide area. In such cases an areal spatial unit has the advantage that it allows cause and effect to reside within the same spatial unit. However, a possible disadvantage of large (but not small) areal units is aggregation error, whereby area averages do not reflect the variety of roads and traffic to be found within them. It is the modeller's task to balance these strengths and weaknesses.

To the extent that data are available, the modeller should choose the spatial unit which best suits the kind of intervention being analysed. Most road agencies maintain electronic databases in which each record relates to a segment or point on the road network. However, it is rare to find other types of data available like this. For instance crash data are not yet readily available in New Zealand by road segment. This is changing as data agencies of all kinds adopt spatial databases, which offer the user great flexibility in specifying spatial units.

Benefit function

The benefit function is a mathematical relationship between (1) the amount of benefit to road users on a given part of the road network, and (2) the amount of intervention carried out on it. Marginal benefit is the rate of change of total benefit with respect to the cost of improved road engineering on a particular road segment depends only on the number of (say) intersection improvements carried out.

Optimality condition

Optimality occurs when the marginal benefit–cost ratio of each intervention in each spatial unit equals the optimal ratio k:

$$\frac{\partial B_{ij}}{\partial Q_{ij}} \Big/ \frac{\partial C_{ij}}{\partial Q_{ij}} = k \qquad (3)$$

where k equals unity when there is no resource constraint. Differentiating equations 1 and 2 with respect to the amount of intervention, and substituting in equation 3 we have

$$f'(V_i, Q_{ij}, D_i) \Big/ g'(Q_{ij}) = k \qquad (4)$$

Road safety model

We are now in a position to adapt the generalised model to the allocation of road safety resources. By limiting its scope we can also simplify it somewhat. The resulting model accords with the logic embodied in *Safety Directions (2nd edition)* (LTSA, 1996). The road safety model applies to the enforcement and engineering aspects of road safety. Other types of road safety expenditure (such as licensing, vehicle standards, education and publicity) are excluded because their impact is largely non-spatial.

Spatial unit

The following discussion applies in principle to any spatial unit—point, road segment or zone—but for ease of exposition the discussion is in terms of road segments.

Benefit function

Road safety interventions take effect by reducing risk. Thus the benefit function is

$$B_{ij} = V_i \; r_j(Q_{ij}, D_i) \qquad (5)$$

This states that the benefit B_{ij} of intervention j in road segment i is directly proportional to traffic volume V_i and the reduction in risk r_j, which is itself a function of the amount of intervention Q_{ij} and the length D_i over which it is applied. This benefit function implies that if traffic volume doubles, total benefit doubles. If the amount of intervention doubles, the effect on total benefit depends on the amount by which risk is reduced as a result. Most interventions can be expected to show diminishing marginal returns; that is, each additional unit of intervention reduces risk by less than the unit before (figure 3, panel 1).

Cost function

The cost of road safety interventions depends on the amount of intervention:

$$C_{ij} = u_j(Q_{ij}) \quad \text{.......... (6)}$$

This states that the cost C_{ij} of intervention j in road segment i is a function of the amount of intervention Q_{ij}. In most cases it will be approximated to a linear function: cost equals the amount of intervention (patrol-hours, say) times unit cost.

Optimality condition

Optimality occurs when the marginal benefit–cost ratio of each intervention in each spatial unit equals the optimal level k:

$$V_i \; r_j'(Q_{ij}, D_i) \Big/ u_j'(Q_{ij}) = k \quad \text{.......... (7)}$$

This states that the optimal amount of intervention occurs when the ratio of (1) traffic volume times the rate of change of risk with respect to the amount of intervention, over (2) the rate of change of cost with respect to the amount of intervention, equals (3) a constant k not less than unity such that all resources are exhausted (figure 4, panel 1).

Optimality condition—a special case

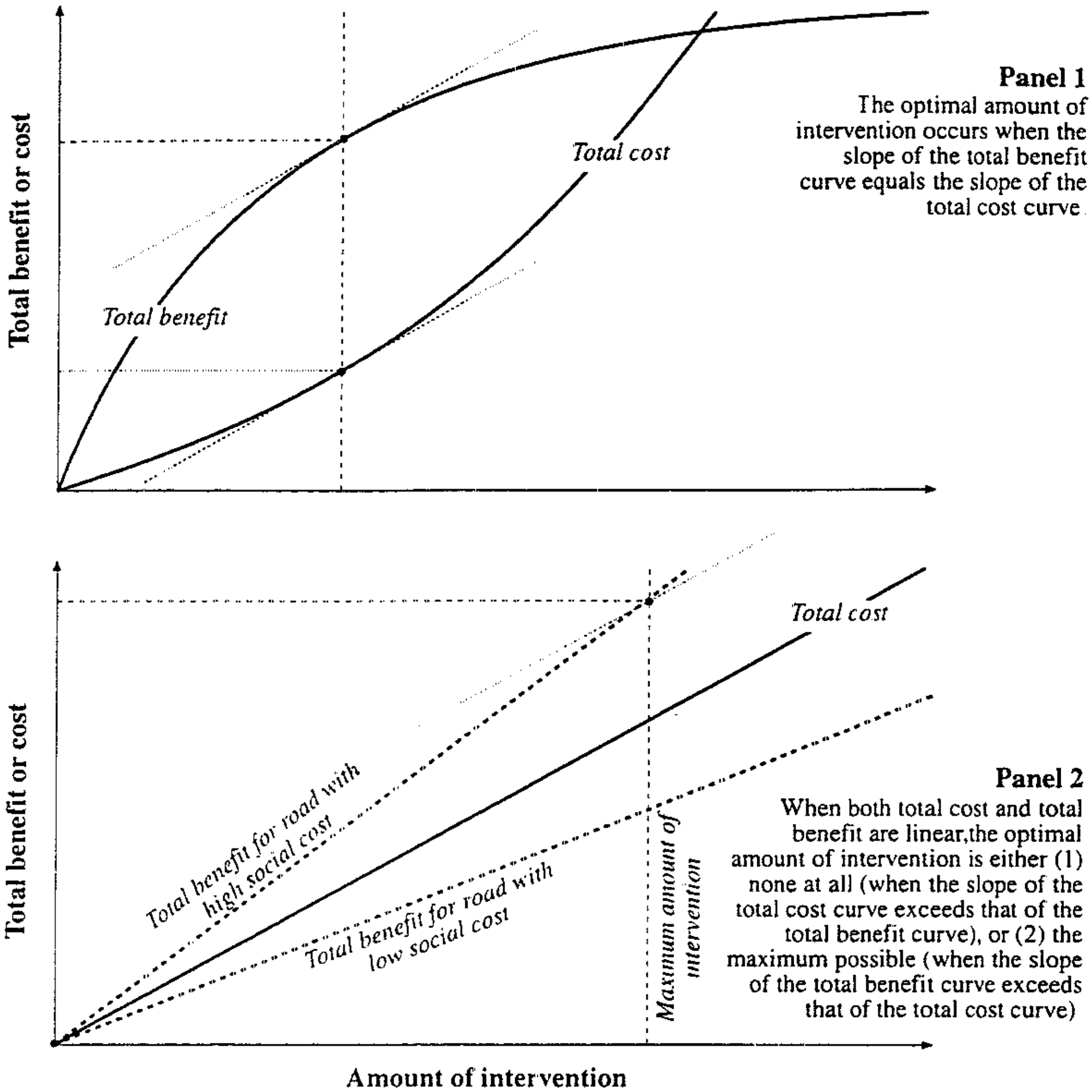
A special case of the optimality condition applies when risk is directly proportional to the linear intensity of intervention (that is, the amount of intervention per unit length of road), and cost is directly proportional to the amount of intervention:

$$V_i \Big/ D_i = F_i = k_j \quad \text{.......... (8)}$$

This states that the optimal amount of intervention is reached when the ratio of traffic volume V_i to road length D_i equals a constant k_j for the type of intervention in question (figure 4, panel 2). Since the ratio of traffic volume to road length is the same thing as traffic flow F_i, we may restate this as follows: under the above assumptions *the optimum amount of a given type of intervention depends solely on traffic flow on the road segment where it is to be imposed.* Where traffic flow exceeds the level implied by equation 8, intervention j should be carried out, otherwise not. Note that optimality does not depend on the amount of intervention Q_{ij}. Thus if warranted at all, intervention j should be carried out to the maximum. This is normally obvious because most interventions are of a binary kind: either they are implemented or they are not.

This reasoning—which applies in principle to safety and non-safety road expenditure alike—is the economic underpinning for the practice of using traffic warrants for engineering treatments. But most importantly it has strategic implications for the allocation of resources over the entire road network.

Figure 4 **Optimality conditions**



Note For ease of illustration this figure relates to the case where the required benefit–cost ratio equals unity. that is, when there is no resource constraint Where resources are constrained the slope of the total benefit curve should exceed the slope of the total cost curve by a factor equal to the amount of the required benefit–cost ratio

Enforcement model

In this section we show how the model is applied to the enforcement of road safety by police patrol. The model was first applied in this area because enforcement accounts for a very large share of the road safety budget, and because it is part of the LTSA's function to advise on enforcement

Spatial unit

The enforcement model uses as its spatial unit New Zealand's 74 local government areas known as Territorial Authorities

Benefit function

We specified the following benefit function both on theoretical grounds (see below) and because it has a greater explanatory power ($R^2 = 90\%$) than others which we tried.

$$B_i = \left(\sum_j \beta_j V_{ij}\right) \theta Q_i^{\alpha} F_i^{\gamma} \qquad (9)$$

Hence marginal benefit is given by

$$\frac{\partial B_i}{\partial Q_i} = \left(\sum_j \beta_j V_{ij}\right) \alpha\theta Q_i^{\alpha-1} F_i^{\gamma} \qquad (10)$$

Equation 9 states that the benefit B_i in Territorial Authority i is a multiplicative function of (1) a linear function of traffic volume V_{ij} in zone i for road type j, (2) a power function of the amount of intervention Q_i in Territorial Authority i, and (3) a power function of average traffic flow F_i in Territorial Authority i.

- *Traffic volume.* We specified a linear relationship between traffic volume and benefit, which implies that the road safety risk per vehicle-km is unrelated to traffic volume. How true is this? Newbery (1990) concludes that risk increases with traffic as a consequence of increased interaction between road users of all kinds. This is undoubtedly so at low traffic densities; but as traffic grows, congestion increases, average speeds fall, and crashes become less likely and (when they occur) less severe. The two tendencies counteract. It is a common practice therefore to assume that the risk remains constant at the national level (see for example Jones-Lee (1990)).

  Territorial Authorities contain roads of widely disparate types which may respond differently to road safety interventions. In the generalised model, which may be based on the road segment, these differences in response may be embodied in parameters. In our enforcement model, which is based on areal spatial units, this is not possible. Instead we adopt a model specification which allows traffic on different types of road to be weighted differently.

- *Amount of intervention.* We specified a power function for the amount of intervention because it accords with how patrol activities operate—that is, each successive unit of intervention has less impact than the one before. The first hour of patrol is more beneficial than the last because it can be implemented when crashes are most frequent; subsequent patrol hours exhibit diminishing marginal benefit up to a theoretical maximum of 24 hours in every day.

- *Traffic flow.* Although traffic flow is not a variable in the generalised model, it is defined as traffic volume divided by the size of the spatial unit (in this case measured by total road length), both of which *are* variables in the generalised model. We hypothesised that the average traffic flow on roads in Territorial Authorities would affect the productivity of police operations, and hence the benefit they produce; for example, enforcement in urban areas, with their high average traffic flows, is generally more productive than enforcement in rural areas. We specified a power function because it implies (as theory suggests) that marginal benefit declines as average traffic flow increases.

Cost function

The marginal cost of police enforcement is given by the unit cost of keeping a patrol car on the road. This parameter is expressed in units of dollars per patrol-hour. Thus

$$\frac{\partial C_i}{\partial Q_i} = u \qquad (11)$$

Optimality condition

Optimality occurs when the benefit–cost ratio of the marginal patrol-hour in each Territorial Authority equals the optimal level k:

$$\frac{\left(\sum_j \beta_j V_{ij}\right) \alpha\theta Q_i^{\alpha-1} F_i^{\gamma}}{u} = k \qquad (12)$$

Hence

$$Q_i = \left(\frac{\alpha\theta}{uk}\left(\sum_j \beta_j V_{ij}\right) F_i^{\gamma}\right)^{\frac{1}{1-\alpha}} \qquad (13)$$

Except for the constant k, all unknowns on the right hand side of equation 13 are either known or can be estimated from historical data (see below). However, since we know the total amount of patrol-hours $\Sigma_i Q_i$, we can also solve for k. Hence we can solve for the optimal amount of patrol-hours in each Territorial Authority Q_i.

Estimation of parameters

The parameters in benefit function were estimated from historical data by regressing traffic volume V_{ij}, amount of intervention Q_i, and average traffic flow F_i on to social cost F_i (table 2). The regression equation had the following functional form:

$$S_i = \left(\sum_j \beta_j V_{ij}\right) \left(1 - \theta Q_i^{\alpha} F_i^{\gamma}\right) \qquad (14)$$

The total social cost of injuries and property damage in New Zealand is about $3.4 billion, or about $1000 per person per year. Its key components are loss of life and life quality. The LTSA has defined a value of 'statistical life' for the purpose of valuing loss of life from traffic injuries. Since 1991 this valuation has been based on a willingness to pay survey (Miller & Guria 1991). In common with many other countries (O'Reilly et al 1992) the social cost of loss of life quality is derived as a fraction of the value of statistical life (Guria 1993). The resource costs of police enforcement, medical treatment and property damage are estimated from actual costs.

Table 2 **Estimates of parameters: enforcement model**

Parameter	Interpretation	Value	Significance
α	Exponent of amount of intervention Q_i in police hours	0.01191	<5%
β_1	Coeff't of volume of traffic on urban state highways V_{i1} in 000 veh-km	632.75	<1%
β_2	Coeff't of volume of traffic on urban local roads V_{i2} in 000 veh-km	1703.50	<1%
β_3	Coeff't of volume of traffic on rural state highways V_{i3} in 000 veh-km	671.99	<1%
β_4	Coeff't of volume of traffic on rural local roads V_{i4} in 000 veh-km	849.56	<1%
γ	Exponent of average traffic flow F_i in veh-km per km of road	0.02568	<1%
θ	Coefficient of amount of intervention Q_i in police hours	0.66472	<1%

Results of the enforcement model

We used the enforcement model to estimate the optimal allocation of police resources for each Territorial Authority, and compared them with currently budgeted allocations (figure 5). The results show that many Territorial Authorities are not apparently receiving the optimal amount of police resources. Among the larger Territorial Authorities, Wellington and Dunedin appear to be overprovided and Christchurch underprovided. (At this stage we cannot comment on Auckland because of the way in which the data are classified (see note to figure 5).) Among the smaller Territorial Authorities some are as much as 50% over- or under-provided

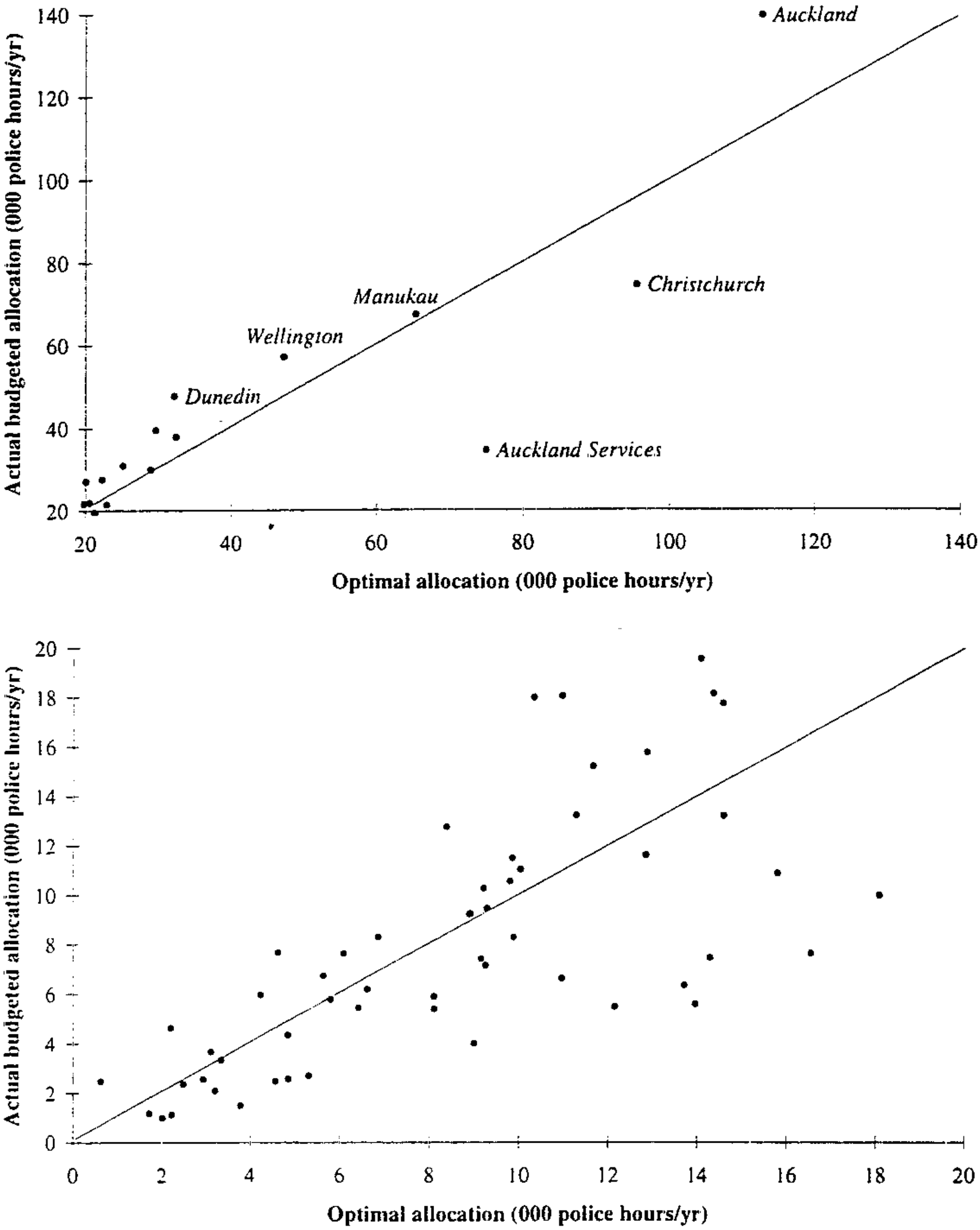
This misallocation of police resources causes a loss of social benefit in that society foregoes reductions in social cost which it could otherwise gain if police resources were to be allocated better. The loss is not large in proportion to the total social cost of crashes, but it is still substantial. There are two main reasons for this. First, even misallocated resources do good—*but not as much good as they could do elsewhere*. Second, the Police are already allocating resources well through the use of existing analytical tools and expert judgment. The purpose of the current exercise is to assist the Police to improve on that, for even a modest proportional improvement on a social cost of over $3 billion is substantial

Conclusions

We have described a tool for allocating resources to the road network in such a way that the benefit to society is maximised. The tool has been applied provisionally to the allocation of police resources for road safety enforcement. We believe that the same general approach has far wider application: it could be beneficially applied to road engineering as well as enforcement, and for non-safety outcomes as well as for safety.

Our approach is characterised by its comprehensiveness. Provided data are available (as is increasingly so as road authorities adopt integrated spatial databases) our approach can be used to examine *all parts of the network simultaneously and continuously*. This brings advantages over the existing *ad hoc* approach to project identification. Our approach therefore provides a valuable complement to existing evaluation tools

Figure 5 **Allocation of police resources for road safety enforcement, 1997**



Notes (1) The solid line on each graph shows the position of each data-point if the actual budgeted allocation were to be optimal Data-points below this line relate to Territorial Authorities which are underprovided with police resources; data-points above the line relate to Territorial Authorities which are overprovided (2) Only the largest Territorial Authorities are labelled (3) 'Auckland Services' is an administrative category employed by the Police to cover resources allocated to motorways in the Auckland area Because of their good safety performance motorways receive few enforcement resources This statistical artifact explains the apparent underprovision to 'Auckland Services' and the corresponding overprovision to Auckland (and perhaps other neighbouring Territorial Authorities) from which motorways have been excluded **Source** LTSA

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