

# Optimising Incident Management on the Road

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## **Abstract**

This article presents a methodology to determine the optimal intensity of Incident Management (IM) on the road in order to reduce time losses of road users. We combine the probability of time loss because of an incident with the expected average time loss in the cost function of the road user. A new element is that the elasticity of demand is included in the model. The change in welfare because of IM will be overestimated if the elasticity of demand is not included in the model. In a numerical example, we show that this overestimation can increase by up to 30 per cent for roads where the number of road users is close to capacity. Therefore, there can be a risk of overinvesting in IM.

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## 1.0 Introduction

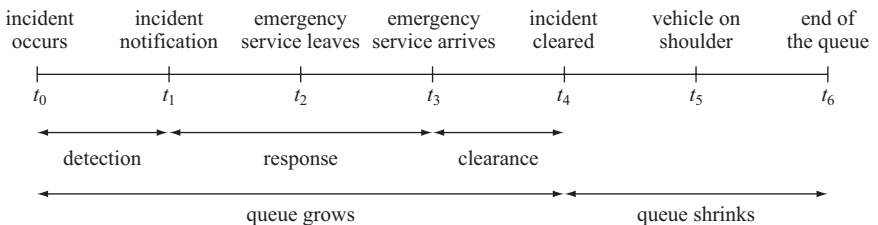
This study presents a methodology to estimate the benefits of policies that reduce incident-related congestion. The main objective of this paper is to include the elasticity of demand in the model that is used for estimating these benefits. Earlier studies assumed inelastic demand, and therefore the lower travel costs because of less incident-related congestion have no effect on the number of travellers on the road. We use a simple model for one road to show the implication of the assumption of inelastic demand.

Incidents on roads result in non-recurrent congestion and longer travel times for road users. Governments try to minimise the effects of incidents by means of Incident Management (IM) which has two goals. The first goal is reducing the incident duration. Lower incident durations result in lower time losses for road users. The second goal is to improve the safety of the people that are involved in the incident, for example, emergency service personnel. In this paper we analyse the benefits of the first goal of IM. We show how the elasticity of demand affects the benefits of IM and therefore the optimal intensity of IM. We summarise the stages of the IM process in Figure 1.

In Figure 1 the detection time is given by  $t_1 - t_0$ . The response time of the emergency vehicle is given by  $t_3 - t_1$ . Finally, the incident clearance time is given by  $t_4 - t_3$ . The incident duration is the sum of the detection time, the response time, and the clearance time  $t_4 - t_0$  (Nam and Mannering, 2000). During this time period the capacity of the road is lower than in the normal situation. If the number of road users is higher than the reduced capacity, this will result in a queue.

Besides the study of Nam and Mannering (2000) there are other studies that investigate the factors that determine the duration of the incident. For example, Lee and Fazio (2005) show that the response time depends on the severity of the crash. Crashes with only property damage

**Figure 1**  
*Stages of the IM Process*



had 20 per cent longer response times than crashes with injuries and fatalities. Also, Hall (2002) analyses response times by accounting for spacing between interchanges and a penalty for changing directions.

Other studies investigate the benefits of IM. Bertini *et al.* (2004) show that there are several types of benefit because of IM. Besides reduced time-losses there are also environmental benefits and safety benefits because of a reduction in the number of secondary incidents. Skabardonis *et al.* (1998) show in a cost–benefit analysis that the freeway service patrol in the Los Angeles area is cost effective. Carson *et al.* (1999) calculate the cost-effectiveness of incident response teams in Washington State. They both find that the benefits are four times higher than the costs. Guin *et al.* (2007) find that the benefits of the implementation of an IM programme, that is part of an advanced transportation management system, are 4.4 times higher than the costs.

In the Netherlands there are four studies that investigate the effects of incidents and the role of IM. Schrijver *et al.* (2006), Kouwenhoven *et al.* (2006), and van Reisen (2006) estimate that approximately 20 per cent of all queuing is due to incidents. Schrijver *et al.* (2006) calculate that without extra IM, the time losses because of incidents would be 65 per cent higher and conclude that IM is very cost-effective. Finally, Wilmlink and Immers (1996) show that IM strategies can reduce incident-related congestion costs by nearly one-half. All studies analyse the benefits of IM in a framework of inelastic demand.

An incident is a stochastic event. This event is determined by three factors. First, the characteristics and the behaviour of the road users affect the incident probability. Examples are alcohol use or the age of the driver (Alexander *et al.*, 2002). The second group of factors are the external factors, such as the road characteristics or the weather conditions. Finally, the number of incidents depends on the number of road users. The analysis of Shefer and Rietveld (1997) shows that the number of incidents is increasing in the number of road users, but if congestion is extreme, the number of incidents will be decreasing and the severity of accidents is less. One can imagine that in a gridlock situation there will be fewer incidents than when people are driving at a higher speed. Peirson *et al.* (1998) and Noland and Quddus (2005) investigate the relationship between incidents and traffic flow and find that the number of incidents is increasing in the number of road users.

The remainder of this paper is organised as follows: in Section 2 we model the time losses in the event of an incident. Section 3 analyses the probability of time losses because of an incident in more detail, taking into account the relationship between traffic flow and the number of incidents. In Sections 4 and 5 the probability of a time loss because of an

incident, and the resulting average time loss, are combined in an average cost function for the road user. This cost function is used to calculate the change in social welfare if more intensive IM is introduced. Section 6 shows how the optimal intensity of IM can be determined, and how the elasticity of demand changes the optimal intensity of IM.

## 2.0 Modelling Time Losses in the Event of an Incident

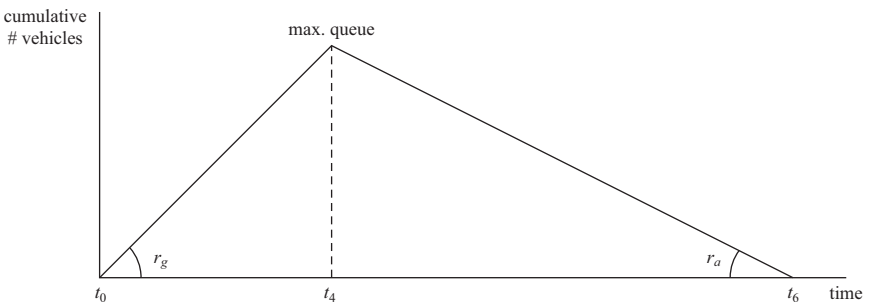
In this section a model is introduced for a single road from *A* to *B*. On this road there is only congestion because of incidents. The incident duration (ID) is a variable in the model and can be influenced by IM. The length of the queue behind the incident is a function of the incident duration and the growth factor of the queue, as shown in Figure 2 (Hall, 1993).

The incident occurs at time  $t_0$  and ends at time  $t_4$ , therefore the ID is equal to  $t_4 - t_0$ . At time  $t_6$  the queue ends. The *y*-axis shows the number of vehicles in the queue. The queue grows by a growth factor,  $r_g$ . This growth rate is equal to the number of entering road users, that is, the flow,  $F$ , minus the capacity after the crash,  $C_{crash}$ . We assume that  $F$  is constant over time. Both  $F$  and  $C_{crash}$  are measured in vehicles per minute. If the incident is cleared, the queue will shrink with shrink rate  $r_a$ , which is equal to the normal capacity,  $C$ , minus  $F$ . Hall (1993) shows that the total time loss is given by equation (1):

$$TTL(ID) = \frac{1}{2} \times r_g \times ID^2 \times \left( 1 + \frac{r_g}{r_a} \right). \tag{1}$$

If IM is introduced, ID will decrease. There is a quadratic relationship between the total time loss and the incident duration. The reason is that

**Figure 2**  
Total Time Loss in Case of an Incident



per minute the duration of the queue increases, and so does the number of travellers who are involved in the queue. Equation (2) shows the marginal change in the total time loss if the ID changes:

$$\frac{\partial \text{TTL}}{\partial \text{ID}} = \text{ID} \times \left( r_g + \frac{r_g^2}{r_a} \right). \quad (2)$$

The effect of IM is higher on roads with a small shrink rate,  $r_a$ . For these roads the normal flow is close to the normal capacity. Second, the effect is higher on roads with a higher growth rate of the queue. Third, for longer incidents the effect of IM is higher. Equation (1) shows the total time loss in the event of an incident. To calculate the average Time Loss (TL) per road user, we divide the total time loss by the number of road users which is equal to  $(t_6 - t_0) \times F$ .<sup>1</sup> In equation (3) the average individual time loss per road user affected by the incident is derived:

$$\begin{aligned} \text{TL}(F, \text{ID}) &= \frac{\text{TTL}(\text{ID})}{F \times \text{ID} \times \left( 1 + \frac{r_g}{r_a} \right)} \\ &= \frac{1}{2} \times \text{ID} \times \frac{r_g}{F} = \frac{1}{2} \times \text{ID} \times \left( 1 - \frac{C_{\text{crash}}}{F} \right). \end{aligned} \quad (3)$$

The average time loss per road user is lower if the ID decreases, and if the ratio of  $C_{\text{crash}}$  and  $F$  is smaller. Equation (3) will be used in the average cost function of the road user.

### 3.0 Incident Probabilities

The incident probability depends on the traffic flow  $F$ . This empirical relationship is frequently estimated in accident prediction models (see, for example, Greibe, 2003; Hiselius, 2004; Caliendo, 2007). Different types of incident have a different relationship with the flow  $F$ . We specify the relationship between the number of incidents and the traffic flow in equation (4):

$$N(F) = \lambda \times F^\gamma + \kappa \times F + c. \quad (4)$$

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<sup>1</sup>Equation (3) is always larger than zero because  $F > C_{\text{crash}}$ , otherwise the time loss is 0. Note that the capacity  $C$  drops out, but that it affects the time loss by  $C_{\text{crash}}$ . It is also possible to specify  $C_{\text{crash}} = \rho \times C$  with  $0 \leq \rho \leq 1$ . Note also that when  $C_{\text{crash}} = 0$ , the average time loss of the drivers involved is simply equal to  $0.5 \times \text{ID}$ .

Equation (4) includes three types of incident: exogenous events, one-sided incidents, and two-sided incidents. The *exogenous events* have no relationship with the flow  $F$  and are given by  $c$ . Examples are bad weather or a collapsing bridge. These types of event occur independently of the number of road users. For the *one-sided incidents* there is a proportional relationship given by  $\kappa \times F$ . The breakdown of a car falls into this category. If there are more cars on the road, the probability of a breakdown of one of these cars increases proportionally. Finally, the relationship between *two-sided incidents* and the traffic flow is described by  $\lambda \times F^\gamma$ . Dickerson *et al.* (2000) show that if there are  $F$  cars on the road, every car can crash into another car, so the probability is proportional to  $F \times (F - 1)/2$ . Therefore, the value of  $\gamma$  is expected to be between 1 and 2 if travellers do not change their behaviour if there are more cars on the road. From equation (4) we can derive the marginal accident rate (Vickrey, 1968; Jansson, 1994):

$$\frac{\partial N(F)}{\partial F} = \gamma \times \lambda \times F^{\gamma-1} + \kappa. \quad (5)$$

Equation (5) shows how the number of incidents is affected by a change in the number of road users. Since  $\gamma$ ,  $\kappa$ ,  $\lambda > 0$  we find the number of incidents is increasing in  $F$ . The number of incidents  $N(F)$  can be used to determine the probability that a driver on the road is confronted with a time loss because of an incident. This probability depends on the period of queueing  $t_6 - t_0$  shown in Figure 2 and the number of incidents  $N(F)$ . Equation (6) shows the relationship between  $p(F)$  and  $N(F)$ , where  $N(F)$  is the number of incidents per year:

$$p(F) = \frac{N(F) \times (t_6 - t_0)}{60 \times 24 \times 365}. \quad (6)$$

The numerator indicates for a certain road how many minutes per year that there is a queue because of an incident.<sup>2</sup> The denominator indicates how many minutes there are in one year. The ratio between the two is the probability that a driver on the road is confronted with a time loss because of an incident.

If the number of incidents increases,  $p(F)$  will increase. But  $p(F)$  is also increasing in the length of the queueing period  $t_6 - t_0$ . The previous insights can be used to derive the expected average-user cost function for someone who travels from  $A$  to  $B$ . We assume that if there is no incident,

<sup>2</sup>To keep the analysis simple, we do not consider overlapping incident spells. Secondary crashes can be included by using  $p(F, ID)$  instead of  $p(F)$ . In that case, the effect of reducing the incident duration also reduces  $p$  and, therefore, the benefits of a reduction in the incident duration will be higher in a model with secondary crashes than in a model without secondary crashes.

the road user faces no congestion, so there is only non-recurrent congestion on this link. The expected average time loss for the road users is equal to the average time loss in the event of an incident,  $TL(F, ID)$ , multiplied by the probability of a time loss because of an incident  $p(F)$ . The expected average costs for a trip from  $A$  to  $B$  are given by equation (7):

$$E(AC) = c_o + \alpha \times (T_f + p(F) \times TL(F, ID)). \quad (7)$$

In equation (7),  $c_o$  is a fixed non-time cost component for the trip made: for example, fuel and toll costs. The travel time for the trip is given by the free-flow travel time  $T_f$ , and the value of travel time is given by  $\alpha$ . The expected average costs are increasing in  $F$  since  $p(F)$  and  $TL(F, ID)$  are increasing in  $F$ .

On the demand side, we assume a linear demand function indicating the willingness-to-pay for the use of the link.<sup>3</sup> If for a certain road user the expected average costs are lower than the willingness to pay, he will enter the road. The demand side of the model is given by equation (8):

$$d(gp) = F = r - b \times gp. \quad (8)$$

In equation (8),  $r$  is a certain constant indicating the flow if the expected average costs are 0, and  $gp$  is the generalised price for using the road. Since we consider only one link, the demand  $d(F)$  is equal to the flow  $F$ . The parameter  $b$  is the slope of the demand curve and shows how sensitive the demand is for changes in the expected average costs. Equation (9) shows the relationship between the value of  $b$  and the elasticity of demand  $E$ :

$$E = \frac{\partial d(gp)}{\partial gp} \times \frac{gp}{F} = -b \times \frac{gp}{F} \Rightarrow b = -E \times \frac{F}{gp}. \quad (9)$$

If the demand curve is flatter, the demand is more elastic. This is important for the welfare analysis in the next section.

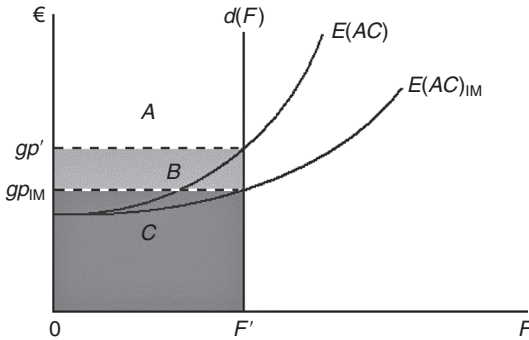
## 4.0 Welfare Analysis

We now have enough elements to determine the optimal intensity of IM. Every intensity results in an incident duration that determines the expected average costs and the demand for trips from  $A$  to  $B$ . The intersection of

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<sup>3</sup>It is also possible to use an iso-elastic demand curve, as done by Arnott *et al.* (1988), but a linear demand curve makes computations easier.

**Figure 3**  
Welfare Change because of a Higher Intensity of IM



the demand curve (equation (8)) with the expected average cost curve (equation (7)) results in a user equilibrium and a corresponding equilibrium price. This section addresses the effect of IM on this equilibrium and the effect of the elasticity of demand. The change in welfare is given by comparing the welfare before and after the introduction of IM.

Figure 3 shows the effect of more IM with inelastic demand. The demand curve is vertical in that case. The expected average cost curve after introducing more IM shifts from  $E(AC)$  to  $E(AC)_{IM}$ , and therefore the equilibrium average costs decrease from  $gp'$  to  $gp_{IM}$ . The equilibrium flow before and after introducing more IM is given by  $F'$ . The demand is equal in both cases because a change in the expected average costs does not affect the number of road users. The change in social welfare<sup>4</sup> is given by the area  $B$  and is equal to  $F' \times (gp' - gp_{IM})$ . In the remainder of this section the assumption of inelastic demand is dropped, and the elastic case is compared with the inelastic case to show the effect of ignoring the elasticity of demand when calculating the social benefits of IM.<sup>5</sup> Figure 4 shows the case where demand is elastic.

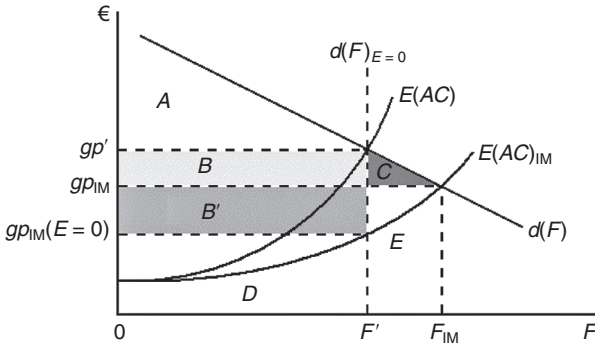
In Figure 4 the expected average costs before the introduction of more IM are indicated by  $E(AC)$ . After the introduction of more IM, the expected average costs for a trip decrease to  $E(AC)_{IM}$ . If demand is assumed to be inelastic the demand curve is given by  $d(F)_{E=0}$ . The intersection with  $E(AC)$  gives the equilibrium generalised price  $gp'$  and the corresponding equilibrium number of trips  $F'$ . After the introduction

<sup>4</sup>The change in social welfare is given by the area under the demand curve minus the total costs. It is assumed that there are no external effects.

<sup>5</sup>For empirical studies about the elasticity of demand we refer to De Jong and Gunn (2001), Goodwin *et al.* (2004) and Graham and Glaister (2004).



**Figure 4**  
 Welfare Change because of more IM with Elastic Demand



of more IM the equilibrium price will decrease to  $gp_{IM}(E=0)$ . The welfare change is indicated by  $B + B'$ . If demand is assumed to be elastic, the demand curve is given by  $d(F)$ . The new equilibrium price is given by  $gp_{IM}$ , and the corresponding number of road users by  $F_{IM}$ . In this new equilibrium, the number of road users is higher because the introduction of more IM results in a lower price for a trip. The welfare change in this case is equal to  $B + C$ .

If we compare the welfare change under the condition of elastic demand with the welfare change under the condition of inelastic demand, we can conclude that there is an overestimation of  $B' - C$  if demand is assumed to be inelastic.<sup>6</sup> If elastic demand is ignored, that there will be more road users is ignored because of the lower price after the introduction of IM. Therefore, there will be an underestimation of welfare corresponding to the area  $C$  related to new road users. But there is also a countereffect. Because of the increase in demand, there will also be an increase in the expected average time loss (equation (3)) and in the probability of time loss because of an incident (equation (6)). Therefore, the entry of new road users results in a lower potential change in welfare for the drivers already on the road ( $B'$ ).

To show how large this overestimation can be, we give a numerical example. We take a road with high capacity use (95 per cent), and a road with average capacity use (75 per cent) because the results differ substantially.<sup>7</sup> The shape of the expected average costs  $E(AC)$  depends on several assumptions as shown in Table 1.

<sup>6</sup>It can be shown that it is always true that  $B' > C$ .

<sup>7</sup>We could also consider a road with a low capacity use, but since the overestimation is very small in that case it is not really interesting in this context.

**Table 1**  
*Assumptions for the Parameters in the Model*

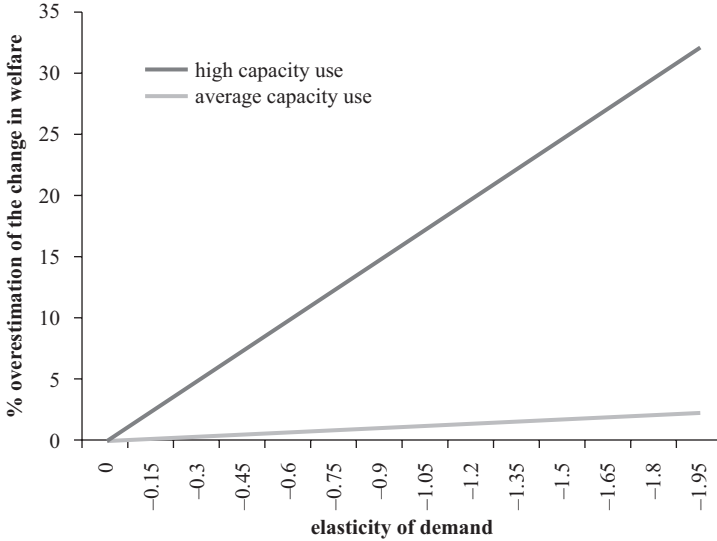
<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Dimension</i>
$E$	Elasticity of demand	between 0 and $-1.95$	
$F'$	Number of road users in equilibrium	high capacity use: 1,725 average capacity use: 1,400	cars/h
$C_{\text{crash}}$	Capacity after the incident	370	cars/h
$c_o$	fixed (non-time) cost component	0.39	eurocent/km
$\alpha$	Value of time	10	euro's/h
ID	Incident duration	35	min
$t$	Reduction of the incident duration	2	min
$L$	Length of the road	20	km
$S$	Speed	100	km
$C$	Normal capacity of the road	1,850	cars/h
$\gamma$	Strength of the relationship between $F$ and two-sided incidents	2	

Hoekstra and Van Zutphen (2005) estimate the number of incidents on main roads in the Netherlands at 17,000 per year. AVV (2007) estimate the number of incidents at 30,000 per year. We adopt an intermediate value of 25,000 incidents per year, that is approximately 64 incidents per 20 kilometres. We assume that every type of incident, as we define it in equation (4), represents one third of the total number of incidents. Tseng *et al.* (2005) estimate a VOT of approximately €10/hour. As an upper limit for the generalised cost elasticity we assume  $-1.95$ .<sup>8</sup> Figure 5 shows the overestimation of the change in welfare if the elasticity of demand is assumed to be 0. The  $x$ -axis shows the adopted elasticity.

Figure 5 shows for this numerical example that the overestimation of social welfare can be 25 per cent if the elasticity of demand is assumed to be 0, but it is  $-1.5$  in reality. This result only holds for roads with high capacity use. For roads with an average capacity use the overestimation is small and around 2 per cent. These results are not given to cast doubt on the usefulness of IM. They only show that, because of the elasticity of demand, the potential welfare gain of more IM is smaller than one would expect. In the next section we show the consequences for the optimal intensity of IM.

<sup>8</sup>The elasticity of demand for travel time is estimated by de Jong and Gunn (2001). They find a value of  $-0.39$ . The costs for travel time are approximately one-fifth of the total generalised costs. If we assume additivity of the cost components, the maximum value of the generalised cost elasticity will be  $-1.95$ .

**Figure 5**  
*Overestimation of the Change in Social Welfare because of more IM if the Elasticity of Demand is Ignored (High and Average Capacity Use)*



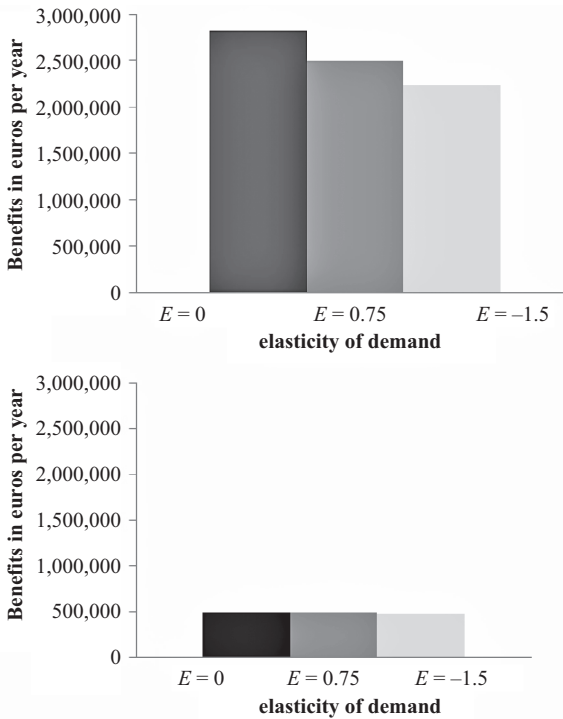
## 5.0 Optimising IM

In this section we use the insights of the previous section to determine the optimal intensity of IM for two policy options: extra ICT and extra emergency services. ICT improves the communication during the IM-process and therefore reduces the incident duration (Wagtendonk *et al.*, 2005). The fixed costs for introducing ICT are high, but the marginal costs are low. An example of ICT policy is introducing automatic detection of incidents with cameras (Versavel, 1999). Suppose this reduces the ID by one minute: its benefits are given in Figure 6.<sup>9</sup> These benefits must be higher than the introduction costs to make the introduction of cameras welfare-improving.

Figure 6 shows that for roads with capacity use and  $E = -1.5$ , the introduction costs must be lower than €2.25 million per year. If the elasticity of demand is ignored ( $E = 0$ ), the maximal introduction costs are €2.83 million per year. When inelastic demand is assumed, the introduction of extra ICT is more likely than if elastic demand is included. This result is consistent with our findings in Section 4.

<sup>9</sup>We use the assumptions of Table 1.

**Figure 6**  
*Benefits of Automatic Detection of Incidents for Two Roads (High and Average Capacity Use)*



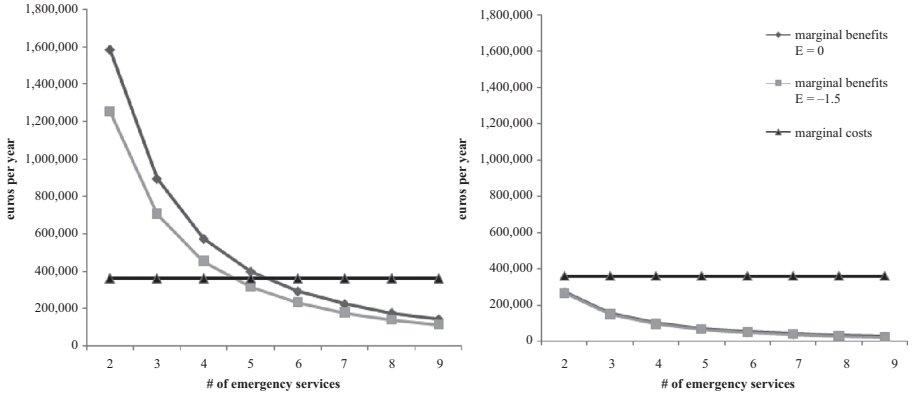
For roads with average capacity use the overestimation is smaller (2 per cent). Also, the change in welfare is five times lower than for roads with high capacity use. This result shows the importance of the differentiation of IM. Roads with higher capacity use must have a higher intensity of IM, since the potential change in welfare is much higher.

The second policy option is introducing extra emergency services. The fixed costs are in this case relatively low, but the marginal costs are high. If extra emergency services are introduced, the effect of an extra emergency service depends on the number of emergency services already in use. The effect of the second emergency service will be higher than the effect of the third vehicle. Suppose that we have a road between  $A$  and  $B$  with length  $L$ . The probability of an incident is homogenously distributed along the road. We assume that the distance to this link for an emergency service is equal to 0.<sup>10</sup> Therefore, the emergency services are positioned

<sup>10</sup>We assume that the constant distance to the link  $L$  is 0. Since we work with the marginal response time, the constant will drop out if we take the first derivative of the average response time.

**Figure 7**

*Optimal Number of Emergency Services for Two Roads (High and Average Capacity Use)*



along the road. The average response time is given by equation (10), where  $ES$  is the number of emergency services. Equation (11) shows the marginal response time:

$$ART = \frac{1}{(2 \times ES + 2)} \times \frac{L}{S}, \tag{10}$$

$$MRT = \frac{\partial ART}{\partial ES} = -t = -\frac{1}{(2 \times (ES + 1)^2)} \times \frac{L}{S}. \tag{11}$$

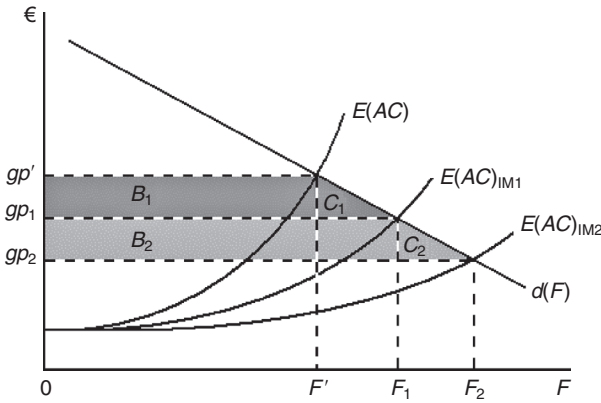
In equations (10) and (11),  $S$  is the speed of the emergency service and  $t$  the reduction of the ID. With this reduction we can calculate the change in welfare for an extra emergency vehicle. We can compare this welfare change with the marginal costs (MCs) of introducing an extra vehicle.<sup>11</sup> If the marginal costs are higher than the marginal benefits, the introduction is not profitable. Figure 7 shows the optimal number of emergency services for different values of the elasticity of demand.<sup>12</sup> We assume that in the initial situation there is already one emergency service in use.

The introduction of the second emergency service results in the highest reduction of the ID and, therefore, in a higher welfare change. For roads with high capacity use, the optimal number of emergency services in this example is equal to 5 if the elasticity of demand is assumed to be 0. If the elasticity of demand is assumed to be  $-1.5$ , the optimal number

<sup>11</sup> Costs for the car and the equipment: €50,000. We assume depreciation in five years, so we have fixed costs of €10,000 per year. The 24-hour use of an emergency vehicle is very labour intensive. There are 5 ftes (1,700 hours per year) needed to use the car 24 hours per day. Wage costs (including training costs) are approximately €70,000 per year. Total costs: €5 × 70,000 + 10,000 = 360,000 per year.

<sup>12</sup> Again we assume the values of Table 1.

**Figure 8**  
Welfare Change for Two Independent IM Policies



of emergency services is equal to 4. Therefore, there is a risk of over-investing in IM policy if the demand is assumed to be inelastic in welfare analysis. For roads with an average capacity use, the introduction of the second emergency service is not profitable, since the marginal costs are higher than the marginal benefits. The elasticity hardly influences the estimated welfare changes in the latter case.

Finally, these results show again the importance of the differentiation of IM policy, since the estimated marginal benefits of a second emergency service are 4.7 times higher for roads with a high density compared with medium density. Therefore, the effect of an extra emergency vehicle will be higher for roads where the number of road users is close to capacity.

**5.1 Combination of ICT and emergency services**

Finally, we show the effect of combining both policies. First, ICT is introduced, and therefore the ID changes. Then, we use the new ID and the new equilibrium situation as a starting point to determine the optimal number of emergency services. We take the parameter values of Table 1 as the starting situation. Our analysis shows that the introduction of ICT has a positive effect on the welfare change because of an extra emergency service. The reason for this result is that, after the introduction of ICT, there will be more road users that benefit from the introduction of an extra emergency service. Figure 8 shows this mechanism.

Two equivalent policies are introduced. Both reduce the incident duration by  $t$ .<sup>13</sup> First the equilibrium average costs drop from  $gp'$  to

<sup>13</sup>The reduction  $t$  does not necessarily have to be the same for both policies.

$gp_{IM}$ . The new equilibrium number of users is given by  $F_1$ . The area  $B_1 + C_1$  gives the change in welfare because of Policy 1. The second policy results in the equilibrium average costs  $E(AC)_{IM2}$  and a new equilibrium number of users of  $F_2$ . The welfare gain is equal to  $B_2 + C_2$  and is clearly bigger than  $B_1 + C_1$ . Or, in other words: Policy 2 is more effective because the lower ID of Policy 1 results in a higher number of users. This super-additivity is remarkable since in most policy analysis on traffic incidents, there is sub-additivity, meaning that the effect of one policy reduces the effect of another policy. The reason for this super-additivity is that more IM results in a higher demand.

## 5.2 Discussion

It is clear that we have kept our model simple in order to be able to address the research question in a transparent way. For real-world applications the model would have to be extended in several directions. We will discuss a number of such possible extensions in this section. They relate to: the inclusion of recurrent congestion, perception issues, heterogeneity of transport flows, scheduling costs, and accident costs. In terms of the type of congestion considered, we only address non-recurrent congestion. Recurrent congestion could have been incorporated in the model, for example, by means of a time-independent congestion model, or a time-dependent bottleneck model (see, for example, Lindsey and Verhoef, 2008). This would lead to additional complexity since in the case of elastic demand, incident management would not only have an impact on travel times during episodes when incidents occur, but also on travel times in the absence of incidents.

A related issue is that with non-recurrent congestion, information and perception issues may become relevant. In particular, one might argue that in the absence of information on incidents, the elasticity of demand may approach zero. Note, however, that during the peaks, most drivers are commuters, implying that they are frequent road users, so that they have been able to collect a considerable record of observations of travel times by experience during a longer period; hence, it is safe to assume that they are well informed on probabilities of incidents and the ensuing delays. Further, less frequent users of the road may transfer their experience about non-recurrent delays in some road segments to other segments. It is clear that perception errors may occur here, since travellers do not have perfect knowledge about the probabilities or simply do not understand probabilities. An interesting direction for future research is therefore how the measured probabilities are related to the perceived probabilities of the travellers and their travel experience.

In the present model we also ignore the issue of heterogeneity of traffic; in particular, we ignore the coexistence of trucks and passenger cars on the same roads. The effects of heterogeneity on average speeds and probabilities of incidents have been analysed in Rietveld and Shefer (1998), among others. To incorporate this aspect into our model, we would have to formulate demand for two or more groups of users in combination with the ‘technology’ of the use of infrastructure by different user groups and the possible interferences between them.

Scheduling costs are not included in this model as we only address the expected delay of an incident. Anticipating behaviour because of variable travel times as analysed by Peer *et al.* (2009a) is therefore not included. However, our model may not be that restrictive for two reasons. First of all, expected delay and the standard deviation of the delay are strongly correlated, as shown by Fosgerau and Karlström (2009) and Peer *et al.* (2009b). Peer *et al.* (2009b) show that there is almost a linear relationship between expected delay and the standard deviation of the delay. Furthermore, Fosgerau and Karlström (2009) show that scheduling costs are linearly related to the standard deviation. Therefore, expected delay may be a good proxy for generalised costs even when scheduling costs are omitted.

Another limitation of the model is that we do not include the benefit of extra lives saved. The expected average costs in equation (7) can be extended by including an extra term for costs of casualties due to an incident. An intensification of IM will therefore reduce the time until clearing starts which is indicated as  $t_3 - t_0$  in Figure 1. This may have a positive impact on the probability for seriously injured road users to recover from their injuries and therefore on the corresponding expected costs of an incident. The estimated benefits of IM are in that case higher than in the model we have presented.

A related point is that severity of accidents may be affected by speed levels (Shefer and Rietveld, 1997). This observation is of particular importance when the model would incorporate congestion, for example, by means of the well-known speed-flow diagrams (Lindsey and Verhoef, 2008). In such a context, speed has become endogenous. This would lead to an additional feedback in the model. Incident management would affect generalised costs as described in equation (7) and hence have an impact on travel demand; travel demand would in turn affect speeds under non-incident periods which would then lead to changes in the severity of accidents.

We conclude that the model can be extended in various directions. These extensions will have an impact on the total costs and benefits of IM, and hence on the optimal IM level. They will also have an impact on



the bias that will be the consequence of ignoring the elasticity of demand. An in-depth analysis of these issues is beyond the scope of this paper. For some of them we have indicated that they will most probably not lead to substantial changes. For others, the consequences are less obvious, however; we leave this as a subject for further research.

## 6.0 Conclusions

In this paper we have presented a simple model to optimise Incident Management (IM) on the road, with special emphasis on its costs and benefits in terms of non-recurrent congestion. Analysing the social benefits in a demand–supply model results in significant lower estimations of social welfare due to more IM, because the lower equilibrium average trip costs result in more demand which has an adverse effect on non-recurrent congestion. The effect of the overestimation depends on the capacity use of the road. Finally, we derive the optimal intensity for two policies: more ICT and extra emergency services. We show that the differentiation of IM is important, since the marginal benefits of IM services for roads with high capacity use are around five times higher compared with roads with medium capacity use. Ignoring the elasticity of demand results in a higher optimal intensity of IM. Therefore, there can be a risk of overinvesting in IM-policy if demand is assumed to be inelastic in welfare analysis.

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