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Traffic safety: speed limits, strict liability and a km tax

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Abstract

Policy makers can improve traffic safety by the use of different instruments. These instruments include regulation (e.g. speed limits, vehicle standards, etc.), enforcement of regulation, liability rules, physical measures (e.g. roundabouts, speed humps, etc.), economic instruments (pricing of transport, insurance pricing), education and sensitisation.

In this paper we focus on two specific determinants of accidents: speed and the number of kilometres people drive. If there is no government intervention, people do not take into account the full cost of their driving and they will drive too fast and too much. In our setting, the government can use three instruments to influence the behaviour of people: speed limits, strict liability and a kilometre tax. We set up a theoretical model of traffic accidents to analyse the choice of the speed level and the number of kilometres under the different instruments and determine the optimal combinations. Given our assumptions we never reach the social optimum. To illustrate our results we discuss a numerical example.

Keywords: transport, law and economic, liability, regulation, accidents

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1. INTRODUCTION

Road accidents are a serious public health problem and impose a serious economic burden. They are estimated to represent up to 4 per cent of GDP in some countries[1]. Therefore it is not surprising that there is intensive activity in many European countries to combat road accidents. The government can use different instruments to improve traffic safety such as regulation (speed limits[2], vehicle standards, etc.) and its enforcement, liability rules (strict liability, negligence), physical measures (roundabouts, speed humps, etc.), economic instruments (road pricing, insurance, etc.), education and sensitisation.

One of the main causal factors of accidents is the behaviour of people; 85 per cent of all accidents are mainly due to road users' error, 10 percent is attributed to imperfect roadway design and other environmental factors and 5 per cent to vehicle defects[3]. Here we focus on the behaviour of people; more particularly, we focus on their choice of speed and on the number of kilometres they drive. We consider three specific instruments: a speed limit, strict liability[4] and a kilometre tax. Car drivers may be induced to drive at a reasonable speed by

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[1] OECD (2002)

[2] Note that speed limits only influence traffic safety if there is no congestion.

[3] Lonero et al. (1995)

[4] Strict liability means that if A damages B, then A is liable for that damage.

letting them bear the accident cost (liability) and/or by setting speed limits and enforcing them (regulation). The activity level, this is the number of kilometres one drives can be influenced by strict liability and by the use of a tax. Indirectly, the activity is influenced by regulation because it is a function of speed.

We use a theoretical model of traffic accidents based on Shavell (1984a)[5] to analyse the choice of speed and activity of people under the different instruments. The aim is to provide rules for the optimal combination of these instruments.

The structure of the paper is as follows. We first explain the assumptions we use to build our model. Secondly, we consider each instrument, strict liability, regulation and a kilometre tax as an instrument on its own. Next, we consider the behaviour of people under combinations of instruments. Note that in the base model we assume that people comply with regulation. This is obvious a strong simplification, which we relax in section five. Next, we illustrate the model with a numerical example. Finally, we conclude.

2. THE MODEL

We consider unilateral accidents. In this kind of accidents only one party, the injurer, can prevent the accident and the other party, the victim, bears all the losses. We assume that the losses can be expressed purely in pecuniary terms. Furthermore, we assume that both parties are risk neutral. Hence there is no need for insurance.

As an example throughout the text, we think of an accident between a bicycle and a car. We assume that only the car driver can take care by adjusting his speed and that if an accident happens only the cyclist experiences the losses[6].

For the individual car driver the cost of driving, *C(x,t)* is a continuous function of speed, *x*, and the value of time, *t*. *C(x,t)* comprises the time cost of the trip (with *t* the value of time), the resource costs and the own accident cost[7]. We assume that the cost of driving for a given value of time decreases with speed: $C_x < 0, C_{xx} > 0$. The cost of driving at a given level of speed is increasing and linear in the value of time, $C_t > 0, C_{tt} = 0$. We also assume that if speed rises, the private cost decreases faster if the value of time is larger, $C_{xt} < 0$. *C(x,t)* reaches a minimum for a given value of *t* at speed $x^t_{private}$. We assume that people differ in their values of time. Hence, their transport cost, given a certain level of speed, will differ. People know their own value of time, but the government only knows the distribution of t[8]. *f(t)* represents the probability density of *t* on [a,b], with *f(t)*>0, $0 \le a < b$.

One of the main assumptions is that the accident costs are only determined by the level of speed and activity of the driver. We denote speed by *x*, $x \ge 0$. By driving more slowly, the car driver can lower the probability of an accident, *p(x)* with $0 \le p(x) \le 1$, *p(0)=0*, *p'(x)*>0, *p''(x)*>0. We assume that the driver has perfect information on this probability function. Furthermore, we assume that the harm, h is the same for all accidents and independent of the level of speed[9]. The harm is known to the regulator.

[5] Shavell's model (1984a) provides a framework which considers regulation and liability as means to control accident risks. We apply this model to traffic safety and extend it by incorporating the activity level, a kilometre tax and imperfect compliance with the speed limits.

[6] In reality, the cyclist also influences the probability of an accident.

[7] Given that we assume unilateral accidents, the own accident costs are zero in our model. See for example Peirson ea (1998) for a discussion of which costs are external and which are internal to the driver.

[8] The value of time is a function of the trip purpose, the income, etc. In the remainder of the text we assume that it only depends on the trip purpose. This trip purpose can change from trip to trip. It is difficult for the government to know the trip purposes of all people; hence it is plausible to assume that the government does not know the individual value of time.

[9] We can make the harm dependent on speed and not the probability or make both dependent. Note that we can write the expected accident costs as $p(x) \cdot h = H(x) = p \cdot h(x) = p(x) \cdot h(x)$

Drivers also influence the accident cost by their activity level. In the literature one denotes as activity level everything that influences the social cost of an accident, but that is not included in a standard of due care set by the courts. Think for example of the number of times one looks into the rear mirror, the number of kilometres one drives, etc. In this setting we restrict the interpretation of the activity level to the number of kilometres one drives[10], which we denote by *ac*. We assume that the driver gets a certain utility of his activity level and that this utility is increasing in a decreasing way in the level of activity, $U'(ac)>0$, $U''(ac)<0$. We also assume that the private costs of driving and expected accident cost rise proportionally with the number of kilometres.

We can now calculate the private and the socially optimal levels of speed and activity.

2.1. Private and social optimum

If neither the level of speed, nor the activity level is controlled for by the government, the driver will maximise his utility, taking into account only his private costs. Each driver will

$$\max_{ac,x} U(ac) - ac \cdot C(x,t) \tag{1}$$

This gives the private optimal level of speed, $x^t_{private}$ and activity, $ac^t_{private}$. The first order condition with respect to *x* gives

$$ac \cdot C_x(x,t) = 0 \Rightarrow C_x(x,t) = 0 \tag{2}$$

The private optimal speed, $x^t_{private}$ equals the minimum of the private cost function. Note that it does not depend on the activity level. Given this speed, the private optimal activity, $ac^t_{private}$ is determined by the first order condition with respect to *ac*:

$$U'(ac) = C(x^t_{private}, t) \tag{3}$$

He will increase his activity level as long as the marginal utility of doing this is larger than the private cost of it.

We maximise social welfare with respect to the level of speed and activity for each value of time and for a given level of harm. The social welfare equals the utility one obtains from the activity, taking into account the private and external cost of driving. Comparing (4) and (1) it is clear that the external cost equals the expected accident costs, $ac \cdot p(x)\overline{h}$.

$$\max_{ac,x} U(ac) - ac \cdot \left[C(x,t) + p(x)\overline{h} \right] \tag{4}$$

Deriving (4) with respect to the level of speed leads to the first order condition

$$C_x(x,t) = -p'(x)\overline{h} \tag{5}$$

This gives the first-best level of speed $x^*(t,h)$. The condition states that, for every *t* and $\overline{h}$, the marginal cost of lowering one's speed should equal the marginal benefit. The marginal benefit equals the marginal (reduction in) accident risk times the harm. We can prove[11] that for a given harm, $\overline{h}$ the socially optimal speed level is an increasing function of the value of time, $x^*_t(t,h) \geq 0$. We can also prove that for a given value of time $\overline{t}$, the socially optimal level of speed is decreasing in the level of harm, $x^*_h(\overline{t},h) < 0$.

Given the socially optimal level of speed, the socially optimal level of activity for each *t* and given $\overline{h}$ is given by

[10] To control the number of kilometres, we can use a kilometre tax. Note that the number of times one looks into the mirror can not be influenced by a tax.

[11] The proofs can be found in appendix A.

$$U'(ac) = C(x^*, t) + p(x^*)\overline{h} \quad (6)$$

In words, the marginal benefit of raising the number of kilometres should cover the private cost of driving and the expected cost of an accident, when driving at the socially optimal speed. We can prove that the socially optimal activity level decreases in the value of time and in the level of harm.

Again, as with the level of speed, when we compare (6) and (3), we see that the private optimum does not equal the social optimum. In the private optimum the driver does not take into account the full costs of driving an extra kilometre.

We conclude that if the government does not influence the behaviour of the driver, nor the level of speed, nor the activity level will be optimal. The driver will drive too fast and too many kilometres. The government can influence the behaviour of the driver by the use of regulation, strict liability and a kilometre tax. We first discuss the instruments used separately. In section three, we consider some combinations.

2.2. Strict Liability

Strict liability means that if an accident happens the car driver is always liable, whatever his level of speed at the time of the accident. This reflects the Belgian legislation on accidents between car drivers and weak road users.

In a perfect world with perfect information, the driver then fully internalises the accident costs and strict liability leads to the optimal solution. The fact that the victim does not carry any losses does not play a role since he has no influence on the probability of an accident. In the real world however, strict liability faces two main problems. The first problem is referred to in the literature as 'judgement proof'. This means that in reality some people cannot pay for the damages they cause[12]. Given an estimate for the value of a life of 1.670.000 euro[13], this is not unrealistic. The same effect on the behaviour of people results if they do not have to pay the full damages. This is not an unrealistic assumption as courts often make wrong estimates. Judgment proof makes that drivers do not take into account the full accident cost. A second problem is the fact that the probability of being held liable is not always equal to one. Think for example of hit and run drivers. Again, this means that people do not take into account the full accident cost. If drivers underestimate the probability of an accident or overestimate their capabilities, this has the same effect.

Denote the level of assets by *y*, and the probability of conviction by *q*, $0 \le q < 1$. In this paper we assume that *q* is exogenously given, this is, *q* is not an instrument of the government. We assume that *y* and *q* are the same for all drivers. The injurer pays *h* if $h \le y$, otherwise he pays *y*.

For a given level of harm, $\overline{h}$ and for each value of time, *t*, the car driver maximises his utility taking into account the costs of driving and the expected liability costs. He will

$$\max_{ac,x} U(ac) - \left[ac \cdot \left(C(x,t) + q \cdot p(x) \cdot \min\left\{\overline{h}, y\right\}\right)\right] \quad (7)$$

This leads to $x_L(t, \overline{h})$. Under strict liability, given the harm, the speed at which people drive as a function of their value of time, equals the socially optimal speed with the harm equal to

[12] Remember that we do not take into account the existence of insurance.
[13] UNITE (2001)

$q\min\{\overline{h},y\}$. This level of speed is higher than the actual socially optimal speed given the harm $\overline{h}$ [14]:

$$x_L(t,\overline{h}) = x^*(t,q\min\{\overline{h},y\}) \geq x^*(t,\overline{h}) \qquad (8)$$

We present this case graphically in Figure 1. On the horizontal axis we find the level of speed, on the vertical axis the costs expressed in euro. The upward sloping curves represent the derivative of the private cost functions for each value of time and the downward sloping curve represents minus the derivative of the expected accident cost. Their intersection determines the socially optimal level of speed. Note that for $t_1 < t_2$, $x_1^* < x_2^*$. The private optimal level of speed is determined by the intersection of the derivative of the private cost function with the horizontal axis. The levels of speed under strict liability are given by the intersections of the derivative of the private cost functions and the derivative of the expected liability cost, $-qp'(x)\min\{h,y\}$.

(insert figure 1 about here)

Figure 1 shows that strict liability, used as the only regulatory instrument, causes people to drive too fast with respect to the optimal solution. The reason is that, because of the judgement proof problem and the positive chance of the responsible driver not being sued, they do not take into account the full expected accident cost. Remark that in setting the fine, courts could take into account the fact that q<1 by correcting the fine with a factor *1/q*. This would raise the expected liability cost for the driver, but it also increases the problem of judgement proof.

Given this level of speed, the activity level under strict liability, $ac_L(t,\overline{h})$ will be given by

$$U'(ac) = C(x_L(t,\overline{h}),t) + q \cdot p(x_L(t,\overline{h})) \cdot \min\{\overline{h},y\} \qquad (9)$$

The optimal activity level, given this level of speed, is determined by

$$\begin{aligned} &\max_{ac,x} U(ac) - ac \cdot \left(C(x_L(t,\overline{h}),t) + p(x_L(t,\overline{h})) \cdot \overline{h}\right) \\ &\Rightarrow U'(ac) = \left(C(x_L(t,\overline{h}),t) + p(x_L(t,\overline{h})) \cdot \overline{h}\right) \end{aligned} \qquad (10)$$

Compare (9) with (10). The private costs are equal but the expected accident cost is larger than the expected liability cost. This means that the right-hand side of (10) is larger than the right hand side of (9). Hence the marginal utility of activity should cover a higher cost per unit of activity in the social optimum than under strict liability. Hence he will drive too much under strict liability. This is also shown on Figure 2. On the horizontal axis we denote the activity level, on the vertical axis the costs expressed in euro. The downward sloping curve represents the marginal utility of activity, the horizontal curves the marginal costs of being involved in the activity.

(insert figure 2 about here)

[14]**Proof**: Since (7) is identical in form to (4), it is clear that for all t, $x_L(t,\overline{h})$ is determined by the first equality in (8). To prove the inequality, note that we proved that $x^*(\overline{t},h)$ is decreasing in h and that $h \geq q \cdot \min\{h,y\}$. ■

2.3. Regulation

One of the best known types of regulation in traffic are speed limits. Since speed is the decision variable in our model, we concentrate on this type of regulation. Because of the differences in time values it would be optimal to set a different standard for each value of time. The regulator lacks the information to do this and sets a uniform standard. This is also what we observe in the real world. Following Shavell, we implicitly assume that all parties comply with regulation. Given the number of speed violations, this is not a realistic assumption. It would therefore be interesting to see what happens to the model if we allow for non-compliance. This will be done in section five as an extension, in which we also consider the optimal setting of the fines and the probability of detection.

Denote s as the regulatory standard. The regulator wants to maximise social welfare:

$$\max_{s,ac} U(ac) - \left[ac \cdot \left(\int_a^b C(s,t) f(t) dt + p(s)\overline{h} \right) \right] = \max_{s,ac} U(ac) - \left[ac \cdot \left(E\left[C(s)\right] + p(s)\overline{h} \right) \right] \quad (11)$$

This gives the first order condition with respect to s

$$\begin{aligned} & E\left[C'(s)\right] = -p'(s)\overline{h} \\ & \Rightarrow C'(s, E\left[t\right]) = -p'(s)\overline{h} \qquad \text{(C linear in t)} \end{aligned} \quad (12)$$

This gives s^*, the unique optimal regulatory standard. Note that s^* equals the level of speed that would be first best for the party with the average value of time[15]:

$$s^* = x^*\left(E\left[t\right], \overline{h}\right) \quad (13)$$

This is illustrated in Figure 3. The broken line in Figure 3 represents the derivative of the private cost function for the average value of time. The standard is set at the intersection of the derivative of the expected accident cost function and the private cost function for $t = E\left[t\right]$. For some values of time, such as t_2, the regulation will be too strict, while for others, such as t_1, the regulation is too loose.

(insert figure 3 about here)

In general, the number of kilometres one drives will not be regulated. Given that we assume perfect compliance, the driver will maximise his utility taking into account his private cost of driving at the speed limit.

$$\max_{ac} U(ac) - ac \cdot \left[C(s,t)\right] \quad (14)$$

The number of kilometres under regulation, $ac_s(t, \overline{h})$, is then determined by

$$U'(ac) = C(s,t) \quad (15)$$

The optimal number of kilometres, $ac_s^*(t, \overline{h})$, given the speed limit s is determined by

$$U'(ac) = C(s,t) + p(s) \cdot \overline{h} \quad (16)$$

Comparing (16) with (15), it is clear that the driver does not take into account the expected accident cost in determining the number of kilometres. Hence, he will drive too much.

[15] **Proof**: to prove that $s^* = x^*\left(E\left[t\right], \overline{h}\right)$ compare FOC (5) and FOC (12). s^* is unique since $C_x < 0, C_{xx} > 0$ and $p_x > 0, p_{xx} > 0$. ■

2.4. *Kilometre tax used alone*

A possible instrument to influence the number of kilometres one drives is a tax on the level of activity, tax_{ac}.

The driver will maximise his utility taking into account his private costs and the tax.

$$\max_{ac,x} U(ac) - ac \cdot C(x,t) - ac \cdot tax_{ac}^{t} \tag{17}$$

The level of speed under a kilometre tax, x_{tax}^{t} is determined by

$$C_x(x,t) = 0 \tag{18}$$

This is, under the use of only a kilometre tax, the government will not affect the level of speed and speed will equal the private optimal speed. The government takes this into account in setting the tax.

The number of kilometres under a kilometre tax, ac_{tax}^{t} is determined by

$$U'(ac) = C\left(x_{private}^{t}, t\right) + tax_{ac}^{t} \tag{19}$$

Given the level of speed, the government would like the drivers to determine their level of speed based on

$$U'(ac) = C\left(x_{private}^{t}, t\right) + p\left(x_{private}^{t}\right)\overline{h} \tag{20}$$

Comparing (19) and (20), it is clear that in the optimum the tax equals the external cost, $tax_{ac}^{*} = p\left(x_{private}^{t}\right)\overline{h}$. However, as with regulation, the government faces the problem that it has to set a uniform tax for all drivers, while the socially optimal activity level depends on the value of time. Hence he will set the tax equal to the expected value of the external costs, hence

$$tax_{ac}^{*} = E\left[p\left(x_{private}^{t}\right)\overline{h}\right] \tag{21}$$

The activity level for each driver is then given by

$$\begin{aligned} U'(ac) &= C(x_{private}^{t}, t) + tax_{ac}^{*} \\ &= C(x_{private}^{t}, t) + E\left[p\left(x_{private}^{t}\right)\overline{h}\right] \end{aligned} \tag{22}$$

We represent this graphically in Figure 4 for a driver with value of time $\tilde{t}$.

(insert figure 4 about here)

In general, the level of activity under a uniform tax will not equal $ac_{private}^{*}$, the optimal activity level given that the speed is $x_{private}^{\tilde{t}}$. Ex ante it is difficult to judge what the outcome is. The private cost in (22) and (20) are equal. Whether the driver will drive too much or too little compared to the optimum depends on the magnitude of the tax relative to his expected accident cost. If for a person with a value of time $\tilde{t}$ $p\left(x_{private}^{\tilde{t}}\right)\overline{h} > E\left[p\left(x_{private}^{t}\right)\overline{h}\right]$, the tax will be too low, for example tax_{1}^{*}, and hence he will drive too much. The welfare loss of this tax is presented by the dark grey area. On the other hand, if $p\left(x_{private}^{\tilde{t}}\right)\overline{h} < E\left[p\left(x_{private}^{t}\right)\overline{h}\right]$

the tax is too high, for example tax_2^* and hence he will drive too little. The welfare loss of such a tax equals the light grey area in Figure 4. Note that $p\left(x_{private}^t\right)\bar{h}$ rises in the value of time. Hence people with a low value of time will drive too little and people with a high value of time too much. Both types will certainly drive less than if there is no tax. Given that the tax takes into account that the people drive at their private optimal speed, the tax will be higher than if people would drive at the socially optimal level of speed. Hence the kilometre tax shall correct for some of accidents costs due to speeding.

3. JOINT USE

We now consider three combinations of the instruments, i.e. we analyse the joint use of regulation and strict liability, of regulation and a kilometre tax and of strict liability and a kilometre tax. In this article we mainly present the intuition. For the proofs and the full mathematical derivations we refer to appendix B.

3.1. Regulation and strict liability

Under joint use of regulation and strict liability, drivers must satisfy the regulation and are liable for the damage done if an accident happens. In other words, they are also liable for the damage if they were not speeding at the time of the accident. Their level of speed will be given by $\min\{s, x_L(t,\bar{h})\}$. This is, since we assume full compliance, people will never drive faster than the standard. However, they will drive more slowly than the standard if this minimises their expected cost.

The regulator takes this into account and maximise social welfare, this is he

$$\max_s U(ac) - ac \cdot \int_a^b \left[C\left(\min\left\{s, x_L\left(t,\bar{h}\right)\right\}, t\right) + p\left(\min\left\{s, x_L\left(t,\bar{h}\right)\right\}\right) \cdot \bar{h} \right] f(t)\,dt \qquad (23)$$

Or, equivalently, he should choose between using strict liability alone, regulation alone or using regulation and strict liability jointly. The option which minimises the social costs should be chosen.

$$\max_s U(ac) - ac \cdot \left[\min_s \left\{ \begin{array}{l} \underbrace{\min_{x_L(b,\bar{h})>s>x_L(a,\bar{h})} \left(\int_a^{t(s)} \left[C\left(x_L(t,\bar{h}),t\right) + p\left(x_L(t,\bar{h})\right)\bar{h} \right] f(t)dt + \int_{t(s)}^b \left[C(s,t) + p(s)\bar{h} \right] f(t)dt \right)}_{\text{joint use of regulation and strict liability}}; \\ \underbrace{\min_{s \le x_L(a,\bar{h})} \int_a^b \left[C(s,t) + p(s)\bar{h} \right] f(t)dt}_{\text{regulation alone}}; \underbrace{\min_{s \ge x_L(b,\bar{h})} \int_a^b \left[C\left(x_L(t,\bar{h}),t\right) + p\left(x_L(t,\bar{h})\right)\bar{h} \right] f(t)dt}_{\text{strict liability alone}} \end{array} \right\} \right]$$

(24)

We can prove that three situations can arise. Firstly, it could be optimal to set the standard so low, that no one drives slower than the speed limit. Speed is then only influenced by regulation, while strict liability dictates the activity level. Hence, people drive too much. Secondly, the standard can be set so high that no one drives at the speed limit; they all drive more slowly. In this case the government is actually using only strict liability as a measure. Regulation has nothing to add but cost. In the intermediate case, some people drive at the speed limit while other people drive more slowly. The people that drive more slowly are the people who drove too fast if regulation was used alone. Hence we are left with relatively more people who have to drive too slowly. Hence it is socially better to set the speed limit higher than if regulation is used alone. The activity level is, again, mainly influenced by the strict liability. Which case will occur depends on how badly strict liability is diluted and on the variability of the values of time.

3.2. Regulation and a kilometre tax

Under the joint use of regulation and a kilometre tax, regulation determines the level of speed but not the level of activity; the tax influences the activity but not the speed. The regulation makes that all people have to drive at the same speed. Hence some people drive too slow, others too fast.

Comparing (15) and (16) it is clear that the optimal tax under joint use equals the external cost given a speed level *s*,

$$tax^*_{jr} = p(s)\overline{h} \tag{25}$$

Therefore the driver will then

$$\begin{aligned} &U'(ac) = C(s,t) + tax^*_{jr} \\ &\Rightarrow U'(ac) = C(s,t) + p(s)\overline{h} \end{aligned} \tag{26}$$

Hence, the driver takes into account the full accident cost of driving at a speed level *s*. This means that the joint use of regulation and a kilometre tax leads to an activity level which is optimal given that speed is regulated.

3.3. Strict liability and a kilometre tax

Under the joint use of strict liability and a km tax people are strictly liable if an accident happens and they pay a tax on their activity level.

The kilometre tax does not influence the speed level. The level of speed will only be influenced by strict liability. Hence the driver maximises his utility, taking into account his private costs, his expected liability costs and the tax.

$$\max_{ac,x} U(ac) - ac \cdot \left[C(x,t) + q \cdot p(x) \cdot \min\left\{\overline{h}, y\right\} + tax^*_{jl} \right] \tag{27}$$

The first order conditions with respect to the level of speed are

$$\begin{aligned} &-ac \cdot \left[C_x(x,t) + q \cdot p'(x) \cdot \min\left\{\overline{h}, y\right\} \right] = 0 \\ &\Leftrightarrow C_x(x,t) + q \cdot p'(x) \cdot \min\left\{\overline{h}, y\right\} = 0 \end{aligned} \tag{28}$$

Hence the speed will be as in the case where strict liability was used alone and people drive too fast.

For the driver, the first order condition with respect to the activity level then equals

$$U'(ac) = C\left(x_L\left(t,\overline{h}\right),t\right) + qp\left(x_L\left(t,\overline{h}\right)\right)\min\left\{y,\overline{h}\right\} + tax^t_{jl} \tag{29}$$

Both instruments influence the activity level. Strict liability makes that the driver takes into account part of the accident costs, but because of the two problems we discussed earlier not the full costs. Therefore his activity is already lower than the private optimum. The tax is then optimally set to the remainder of the accident cost of the driver. However the tax is uniform and hence, again, for some the tax is set too high, for others too low.

4. CHOICE OF INSTRUMENTS

Which instrument or which combination should the government choose? The answer depends on the probability of conviction, the level of assets relative to the harm and on the variability of the values of time.

To make things clear, we summarize the results of the analysis in Table 1.

Table 1 : Overview measures

Measure		Speed	Number of kilometres
Strict liability	$q=1, \bar{h} \le y$ $q<1$ and/or $\bar{h}>y$	Optimal Too high	Optimal Too high
Regulation	uniform	$t<E[t]$: too high $t>E[t]$: too low	No influence, hence too high
Kilometre tax	uniform	Too high	Too high/too low
Strict liability ($q<1$ and/or $\bar{h}>y$) + regulation		$t<t(s)$: too high $t \ge t(s)$: too high/too low	Too high
Kilometre tax	+ strict liability	Too high	Too high/too low
Kilometre tax	+ regulation	$t<E[t]$: too high $t>E[t]$: too low	Optimal

In our setting, if there is no judgement proof problem and if the probability of being held liable equals one, strict liability leads to the optimal solution. If strict liability does not work perfectly, both the level of speed and the activity level are too high.

Under regulation, some drive too fast, others too slow. The activity level is not directly influenced under regulation. People choose their activity level, taking into account the private cost of driving at the speed limit, but not taking into account the expected accident cost. Therefore people drive too much.

A kilometre tax used alone does not influence the level of speed and hence people drive too fast. Since the kilometre tax is uniform, some people will drive too much and others too little.

Three situations can occur under the joint use of regulation and strict liability. Firstly, it could be optimal to set the standard so low, that no one drives slower than the speed limit. Speed is then only influenced by regulation; hence some people will drive too slow, others too fast. Secondly, the standard can be set so high that no one drives at the speed limit; they all drive more slowly. In this case the government is actually using only strict liability as a measure. In the intermediate case, some people drive at the speed limit while other people drive more slowly. Again we find that some people drive too slowly, others too fast. The activity level is in the three cases mainly influenced by strict liability. Hence people drive too much.

Under the joint use of a kilometre tax and strict liability people are strictly liable if an accident happens and they pay a tax on their activity level. The kilometre tax does not influence the speed level. The level of speed will only be influenced by strict liability. Hence people drive too fast. Both instruments influence the activity level. Strict liability makes that the driver takes into account part of the accident cost. The tax is then set to the remainder of the accident cost. However, the tax is uniform and hence for some the tax is set too high, for others too low.

Joint use of a kilometre tax and regulation also does not lead to an optimal speed level but the activity level will be optimal. Therefore, if we only care about the activity level this combination should be preferred. However, we have to take into account that, in general, regulation does not lead to the socially optimal level of speed.

If there is only one value of time, it is of course optimal to use regulation and a kilometre tax jointly[16]. If the variability of the values of time is high and if strict liability works almost perfectly, strict liability will be preferred. In general, we should calculate the welfare losses of the different measures and choose the measure with the lowest social cost.

5. IMPERFECT COMPLIANCE AND ENFORCEMENT

In the analysis up to now, we assumed that people comply with the regulation. If there is no enforcement, this will not be true. Even with enforcement, not all people comply. In this extension we go deeper into the theory of enforcement. We base ourselves on the analysis of Polinsky and Shavell (2000).

For this analysis we keep the level of activity fixed. We only focus on the level of speed. Moreover, we focus on the case in which only regulation is used. We still assume that accidents are unilateral, that only the victim has losses and that people are risk neutral. First, we introduce some notation; next, we consider the optimal setting of the fine and the level of detection. Using backward induction we first consider the behaviour of the individual. Given this behaviour, the government will set the fine, the probability of detection and the speed limit in order to maximise the social welfare. Finally, we analyse how imperfect compliance influences the analysis made above.

5.1. Notation

We denote the level of the fine as a function of the level of speed by

$$\varphi(x) \text{ with } \begin{cases} \varphi(x) = 0 \text{ for } x \leq s \\ \varphi(x) > 0 \text{ for } x > s \end{cases} \tag{30}$$

If one drives faster than the speed limit, the fine is positive, if one drives at the speed limit or slower, the fine is zero. Enforcement comes at a cost. There are two kinds of costs, fixed costs, *fe*, and variable costs, *ve*. The fixed costs do not depend on the number of speeders, the variable costs do. An example of fixed costs is the cost of radar control equipment; an example of variable costs is the administrative cost of collecting a fine. The probability of detection of a speeder, $\delta(fe)$ is a function of the fixed enforcement costs, with $\delta'(fe) > 0, \delta''(fe) < 0$. Note that this probability does not depend on the level of speed.

5.2. Behaviour of the driver

Without enforcement, the driver drives at his private optimal speed. With enforcement, an individual speeds if the cost of doing so, taking into account the expected fine, is lower than driving at the regulated speed. Since regulation is used alone, he will not take into account the accident cost. The driver will speed if

$$\begin{aligned} &C(s,t) > C(x,t) + \delta(fe)\varphi(x) \\ &\Leftrightarrow C(s,t) - C(x,t) > \delta(fe)\varphi(x) \end{aligned} \tag{31}$$

He will speed if the difference in private costs, which is the gain of speeding, is larger than the expected fine. There exists a driver with a value of time such that the above holds with equality, this is

[16] However if strict liability works perfectly this also leads to the social optimum. Since we do not consider the costs of the measures, the government is then indifferent.

$$\begin{aligned}&\exists\tilde{t}: C(s,\tilde{t}) - C(x,\tilde{t}) = \delta(fe)\varphi(x)\\ &\text{with}\begin{cases}\forall t \le \tilde{t}: \text{ comply with regulation}\\ \forall t > \tilde{t}: \text{ speed}\end{cases}\\ &\text{and } \tilde{t} = t(\varphi(x)), \text{ with } t'(\varphi(x)) > 0\end{aligned} \tag{32}$$

5.3. *Government*

The government has now three decisions to make. It has to determine the level of detection via *fe*, the level of the fine, $\varphi(x)$ and the speed limit. It will first set an optimal fine, minimising the social costs[17] and taking into account the behaviour of the driver, this is, it will

$$\min_{\varphi(x)}\left[\underbrace{\int_a^{\tilde{t}(\varphi)}\left[C(s,t)+p(s)\overline{h}\right]f(t)dt}_{\text{comply}} + \underbrace{\int_{\tilde{t}(\varphi)}^{b}\left[C(x,t)+p(x)\overline{h}+ve\cdot\delta(fe)\right]f(t)dt + fe}_{\text{speeding}}\right] \tag{33}$$

We use Leibniz rule and obtain the following first order condition:

$$C(s,\tilde{t}(\varphi)) - C(x,\tilde{t}(\varphi)) = (p(x)-p(s))\overline{h} + ve\cdot\delta(fe) \tag{34}$$

Substituting (32) in (34), we obtain

$$\begin{aligned}&\delta(fe)\cdot\varphi(x) = (p(x)-p(s))\overline{h} + ve\cdot\delta(fe)\\ &\Leftrightarrow \varphi(x) = \frac{(p(x)-p(s))\overline{h}}{\delta(fe)} + ve\end{aligned} \tag{35}$$

We conclude that the optimal fine is a function of speed and equals the sum of the difference in expected accident costs due to speeding, corrected for the probability of detection and the variable enforcement costs. Logically, if the harm rises, or the probability of detection decreases or if the variable costs rise, the fine becomes larger. We assume that people can pay the fine.

For the driver with value of time $\tilde{t}$ we find that

$$\begin{aligned}&C(s,\tilde{t}) = C(x,\tilde{t}) + \delta(fe)\varphi(x)\\ &\Rightarrow C(s,\tilde{t}) = C(x,\tilde{t}) + p(x)\overline{h} - p(s)\overline{h} + \delta(fe)\cdot ve\\ &\Rightarrow C(s,\tilde{t}) + p(s)\overline{h} = C(x,\tilde{t}) + p(x)\overline{h} + \delta(fe)\cdot ve\end{aligned} \tag{36}$$

For people with $t > \tilde{t}$ we find that

$$C(s,t) + p(s)\overline{h} > C(x,t) + p(x)\overline{h} + \delta(fe)\cdot ve \tag{37}$$

Hence, the people that speed are people for whom the social cost of driving at the speed level is higher than the social cost of driving faster, corrected for the expected variable costs of enforcement. Hence, it is socially optimal that those people speed. Remember that in the base scenario, the speed limit was too strict for $t > E[t]$ and that we found that

$$C(s,E[t]) + p(s)\overline{h} = C(x,E(t)) + p(x)\overline{h} \tag{38}$$

[17] For this analysis we keep the activity level fixed. Note that maximising utility/welfare then equals minimising private costs/social costs.

Comparing (38) and (36) it is clear that $\tilde{t} > E[t]$. Hence the people that speed $\left(t > \tilde{t} > E[t]\right)$ are people that had to drive too slowly under regulation with perfect compliance.
Given the expression for the optimal fine, the government will set the level of detection, taking into account the costs. He minimises the social costs with respect to the fixed enforcement costs.

$$\min_{fe}\left[\int_a^{\tilde{t}}\left[C(s,t)+p(s)\overline{h}\right]f(t)\,dt+\int_{\tilde{t}}^{b}\left[C(x,t)+p(x)\overline{h}+ve\cdot\delta(fe)\right]f(t)\,dt+fe\right]$$

$$\Rightarrow ve\cdot\delta'(fe)\int_{\tilde{t}}^{b}f(t)\,dt=-1 \qquad (39)$$

$$\Rightarrow \delta'(fe)=-\frac{1}{ve\cdot\left[F(b)-F(\tilde{t})\right]}$$

(39) determines the level of fixed cost, *fe*, and hence $\delta(fe)$. The probability of detection depends on the variable costs, *ve*, the distribution of the values of time and the speed at which the probability of detection increases if the fixed costs increases. We illustrate this graphically in Figure 5. On the horizontal axis we find the fixed costs, on the vertical axis the inverse of the variable costs, corrected for the distribution of the values of time.

(insert figure 5 about here)

In Figure 5 we see that if the variable enforcement costs increase, $(ve_2 > ve_1)$, the optimal fixed enforcement spending decreases, $(fe_2 < fe_1)$, and hence the probability of detection decreases. The expected fine however remains the same, since the fine will then increase. It makes sense that if the variable enforcement increases, the probability of detection decreases, since every time you detect someone you have to pay the variable enforcement costs. If $\tilde{t}$ goes to b, this is there are less people for which it is optimal to drive too fast, the right-hand side of (39) becomes more negative, and hence the fixed enforcement cost increase. If the probability in detection rises faster in *fe*, *fe*,* quite logical, decreases.

5.4. *Effect on previous analysis*

How does the relaxation of perfect compliance influence the analysis? The government still has to determine the optimal speed level. Minimising the social cost with respect to the speed limit, *s*, leads to the following first order condition

$$\min_s \left[\int_a^{\tilde{t}} \left[C(s,t) + p(s)\bar{h} \right] f(t)\,dt + \int_{\tilde{t}}^{b} \left[C(x,t) + p(x)\bar{h} + ve \cdot \delta(fe) \right] f(t)\,dt + fe \right]$$

$$\Rightarrow \int_a^{\tilde{t}} \left[C_s(s,t) f(t)\,dt \right] + p'(s)\bar{h} \int_a^{\tilde{t}} f(t)dt = 0$$

$$\Rightarrow \int_a^{\tilde{t}} f(t)dt \left[p'(s)\bar{h} + \frac{\int_a^{\tilde{t}} \left[C_s(s,t) f(t)\,dt \right]}{\int_a^{\tilde{t}} f(t)\,dt} \right] = 0 \qquad (40)$$

$$\Rightarrow p'(s)\bar{h} + \frac{\int_a^{\tilde{t}} \left[C_s(s,t) f(t)\,dt \right]}{\int_a^{\tilde{t}} f(t)\,dt} = 0$$

Note that the second term equals the mean of the derivative of the private cost, given that the values of time are in the interval $\left[a, \tilde{t}\right]$. Denote this by $\xi\left[C_x(s,t)\right]$ The question is how this second term relates to the left-hand side of (12). Intuitively, given that we take the mean only over 'small' values of time it will be smaller than the mean over the whole interval of values of time. This is shown in Figure 6. In this figure we find the derivative of the expected harm, of the private costs for the lowest, the highest and the average value of time and of the private costs if the values of time are in the interval $\left[a, \tilde{t}\right]$.

(insert figure 6 about here)

We see that the standard if there is enforcement, s_{enf} is lower than the standard if people comply, s_{pc}. Remember that in our base scenario people with a low value of time, $t < E[t]$, drive too fast, while others with a high value of time, $t > E[t]$ had to drive too slowly. Given an optimal fine and probability of detection, people with a high value of time, $t > \tilde{t}(\varphi) > E[t]$ will violate the speed limit and pay the fine. This is socially optimal. Hence we are left with relatively more people who drive too fast than people who drive too slowly. Hence it is optimal to lower the speed limit.

6. NUMERICAL ILLUSTRATION

We illustrate the model with a numerical example. All the prices in the example are for the year 2000. We start with a description of the input. Using GAMS, we then calculate the private and socially optimal levels of speed and activity and the levels of speed and activity under the different instruments. We end with the calculation of the welfare losses to obtain the 'best' instrument and perform a sensitivity analysis.

We consider three types of roads; this is urban roads, interurban roads and highways. This division is based on the current speed limits, which are 120 km/h for highways, 90 km/h for interurban roads and 50 km/h for urban roads. We first calculate the private optimal speed and activity by maximising expression (1). In this illustration, the private cost per kilometre, $C(x,t)$ equals the sum of the resource cost, the fuel cost and the time cost. The resource cost comprises the purchase cost, the insurance, maintenance, etc. We assume that it is independent of the level of speed and equal to 0.23551[18] euro/km. The fuel cost depends on the fuel price and fuel use. Both elements depend on the type of fuel. We assume that 59.4% of the cars drive on gasoline and 40.6% on diesel[19]. The price of diesel equals 0.811 euro/litre, the price of gasoline equals 1.068 euro/litre[20]. The fuel use depends on the fuel type and the speed. Hence we should use a different function depending on the fuel and the road type. The functions are given in Table 2 where x is the speed in km/h.

Table 2 : Fuel use

Fuel type	*Speed range*	*Fuel use (l/km)*
Diesel	10-130 km/h	$0.1377779 - 0.00242356x + 0.000016279x^2$
Gasoline	10-60 km/h (urban)	$0.92027x^{-0.583}$
	80-130 km/h (interurban + highway)	$0.0006365x + 0.0395757$

MEET project (1998), International Energy Agency (2002)

The time cost equals the value of time divided by the level of speed. The value of time depends on the trip purpose. We assume that there are three types of drivers. A first group, 'business', captures the people who are on the road for their job, think for example of salesmen. They count for 6 % of the total number of drivers[21]. The second group, 'commuters' are the people who drive from their home to work and back. They count for 23 %. The last group, 'other', captures all the rest, think for example of tourists, shoppers,… They count for 71 %. The values of time we use are 23.87 euro/h for the 'business', 6.9 euro/h for the 'commuters' and 4.75 euro/h for the 'other'[22].

The utility is a simple 2-level Constant Elasticity of Substitution (CES) function[23]. We assume that people obtain utility from two goods, transport (*ac*) and 'other goods' (*g*). The utility[24] is then given by

$$U = (\alpha^{1/\sigma} ac^{\sigma - 1/\sigma} + (1-\alpha)^{1/\sigma} g^{\sigma - 1/\sigma})^{\sigma/\sigma - 1} \tag{41}$$

In expression (41), the α's are the share parameters that indicate the share of each utility component in the overall utility. We take α equal to 0.12[25]. The σ's are the elasticity's of substitution. They capture the subjective preferences of the consumer. They indicate how much the consumer is willing to give up of one good in order to receive one more unit of the other good, while keeping his utility level constant. We take σ equal to 0.5. The private optima can be found in Table 3.

18 Own calculations based on De Borger and Proost (1997).
19 Ministerie van Verkeer en Infrastructuur (2000).
20 Ministerie van Economische Zaken (2001).
21 To determine the frequencies of the different groups, we divided the number of kilometres travelled by that group by the total number of kilometres travelled. The figures are based on Hubert and Toint (2002).
22 Own calculations based on Gunn et al (1997).
23 Keller (1976)
24 We assume that the price of 'other goods' equals one. Using the budget constraint, $y = C(x,t) \cdot ac + 1 \cdot g$, we can then write (41) as a function of only the activity level, ac.
25 α and σ are taken from Proost ea (1999)

Table 3 : Private optimal speed (km/h) and activity (km)

	Highway		*Interurban*		*Urban*	
	$x_{private}$	$ac_{private}$	$x_{private}$	$ac_{private}$	$x_{private}$	$ac_{private}$
Commuters	101	14.683	101	14.683	70	14.483
Business	144	12.405	144	12.405	70	11.089
Others	91	15.174	91	15.175	70	15.140

Own calculations

We find that the levels of speed are increasing and that activity levels are decreasing in the value of time. Since we assumed that the fuel use on highways and interurban are the same, for a given value of time, the private costs on these roads are the same. Hence the private optimal levels of speed and activity are the same. Note that for urban roads, the level of speed is the same for all user types. This is because we assumed that it is not feasible to drive faster than 70 km/h on urban roads. If we should only minimise the private costs, without taking into account this constraint, they would want to drive much faster.

The socially optimal levels of speed and activity are calculated by maximising the utility taking into account the private cost and the expected accident cost[26]. The expected accident cost equals the harm times the accident risk. The harm depends on the severity of the accident. We consider three types of accidents, accidents with only lightly injured; accidents with severely injured and fatal accidents. For the moment we do not take into account accidents with only material damage. The accident costs of the different types are listed in Table 4.

Table 4 : Accident cost $\left(\bar{h}\right)$

Type of accident	*Cost of accident (euro)*
Light	101.028
Serious	1.358.830
Fatal	2.103.964

Own calculations based on Schwab, N., Soguel, N. (1995)

The accident risk depends on the type of road. Given the number of accidents and the number of kilometre people drive on the different types of roads, we calculate the accident risk per km. The result is given in Table 5.

[26] Expression (4) in the theoretical framework.

Table 5 : Accident risk per km

Risk per km	*Highway*	*Interurban*	*Urban*
Light	$1.97 \cdot 10^{-7}$	$7.83 \cdot 10^{-7}$	$9.57 \cdot 10^{-7}$
Serious	$0.39 \cdot 10^{-7}$	$1.76 \cdot 10^{-7}$	$1.13 \cdot 10^{-7}$
Fatal	$0.08 \cdot 10^{-7}$	$2.80 \cdot 10^{-7}$	$0.13 \cdot 10^{-7}$

Own calculations based on BIVV(2000)

Elvik (2000) provides a function which gives the effect of a change in speed on the accident risk: effect on accident risk = $1-\left(\frac{\text{speed}}{\text{current speed}}\right)^{pr}$ with pr equal to 4 for fatal accidents, 3 for accidents with serious injuries, and 2 for accidents with light injuries.

Given this information we can calculate the social optimum. The results are given in Table 6.

Table 6 : Socially optimal speed (km/h) and activity (km)

	Highway		*Interurban*		*Urban*	
	x^*	ac^*	x^*	ac^*	x^*	ac^*
Commuter	89	14.396	60	13.400	47	12.050
Business	127	11.996	84	10.639	64	9.392
Other	80	14.925	54	14.054	43	12.679

Own calculations

As predicted the social level of speed is increasing in the value of time and smaller than the private optimal levels of speed. The levels of speed and activity on the highway are larger than on the interurban roads. Given that the private costs are the same, this is due to the difference in accident cost. This is reflected in Table 5 where the accident risk on interurban roads is higher for all types of accidents. Notice that some argue that not only the speed level but also the variance is an important factor in the probability of an accident. If we take this into account, the differences in speed between the user types would be smaller[27]. The socially optimal activity level is, as predicted, lower than the private optimum.

To calculate the levels of speed under strict liability, we assume that the level of assets, y, equals 100.000 euro and that the probability of suit, q, equals 0.8. The results are given in Table 7. Given that strict liability is diluted, the levels of speed and activity under liability are higher than the socially optimal levels of speed and activity but lower than the private optimal levels.

[27] Rietveld, P., Shefer, D. (1998)

Table 7 : Level of speed (km/h) and activity (km) under strict liability

	Highway		*Interurban*		*Urban*	
	x_L	ac_L	x_L	ac_L	x_L	ac_L
Commuter	94	14.501	71	13.783	56	12.565
Business	135	12.166	104	11.239	70	9.982
Other	84	15.013	64	14.375	51	13.150

Own calculations

We also calculate the level of regulation. The speed limits listed in Table 8 make that the business people have to drive too slowly, while the others drive too fast compared to the social optimum. Notice that the speed limits almost equal the socially optimal solution for the commuters. Given the large proportion of 'other' we could have expected that the regulation would be closer to their optimal level of speed. Since this would be far too low for the business people a correction is made for their high vale of time. If we compare with the optimal number of kilometres given that the speed is regulated we see that all drive too much because they do not take into account the accident costs. If we compare with the socially optimal activity levels we see that the 'others' and the 'commuters' drive more, while the 'business' drive less. However, the activity levels listed in Table 6 are optimal given that the speed is socially optimal and under regulation this is not the case.

Table 8 : Speed limits (km/h) and level of activity (km)

	Highway		*Interurban*		*Urban*	
	s^*	ac_S	s^*	ac_S	s^*	ac_S
Commuter	87	14.633	59	14.102	46	13.246
Business	87	11.667	59	10.493	46	9.516
Other	87	15.171	59	14.835	46	14.047

Own calculations

Next, we calculate the level of speed and activity under a km tax. Table 9 presents our results.

Table 9 : Level of speed (km/h) and activity (km) under a km tax

	Highway		*Interurban*		*Urban*	
	x_t	ac_t	x_t	ac_t	x_t	ac_t
Commuter	101	14.375	101	12.376	70	11.310
Business	144	12.209	144	10.860	70	9.356
Other	91	14.838	91	12.683	70	11.641
Tax (€/km)	0.015		0.139		0.221	

Own calculations

Given that the tax does not influence the speed, we find that the optimal speed under a km tax equals the private optimal speed. We find a tax equal to 0.015 euro/km on highways, 0.139 euro/km on interurban roads and 0.221 euro/km on urban roads. If we compare the levels of activity under the tax with the optimal levels, we see that this tax is too high for the the ‘others’ and too low for the ‘business’ and the ‘commuters’ on the highway and the interurban roads. Given that people all drive at the same speed on urban roads, the uniformity is not a problem and people drive the optimal amount of kilometres given their speed.

We also looked at three combinations of instruments; this is the joint use of a km tax and strict liability, of a km tax and regulation and of regulation and strict liability. Under a km tax and strict liability, the levels of speed are the same as under strict liability used alone. From Table 10 it is clear that by adding the tax we bring the activity levels closer to the social optimum than under strict liability alone. Note that, because strict liability makes that part of the accident cost is already internalised, the taxes are lower than if only a km tax is used.

Table 10 : Strict liability and a km tax

	Highway		*Interurban*		*Urban*	
	x_{lt}	ac_{lt}	x_{lt}	ac_{lt}	x_{lt}	ac_{lt}
Commuter	94	14.397	71	13.322	56	11.972
Business	135	12.101	104	10.968	70	9.654
Other	84	14.898	64	13.860	51	12.483
Tax (€/km)	0.005		0.027		0.046	

Own calculations

The joint use of regulation and a km tax makes that people drive at the speed limit and, again, that activity levels are closer to the optimum than if regulation is used alone. This is clear from Table 11.

Table 11 : Regulation and a km tax

	Highway		*Interurban*		*Urban*	
	x_{rt}	ac_{rt}	x_{rt}	ac_{rt}	x_{rt}	ac_{rt}
Commuter	87	14.395	59	13.399	46	12.049
Business	87	11.536	59	10.165	46	8.991
Other	87	14.909	59	14.033	46	12.663
Tax (€/km)	0.012		0.040		0.086	

Own calculations

Under regulation and strict liability, the speed limit is higher than if regulation is used alone. The ‘others’ and the ‘commuters’ drive slower than the speed limit on the highways and on the urban roads. On the interurban roads, only the ‘others’ drive more slowly. The activity level is again closer to the social optimum, but still too high. The results are shown in Table 12.

Table 12 : Strict liability and regulation

	Highway		*Interurban*		*Urban*	
	x_{lr}	ac_{lr}	x_{lr}	ac_{lr}	x_{lr}	ac_{lr}
Commuter	94	14.586	71	13.855	56	12.614
Business	130	12.218	71	10.785	70	9.955
Other	84	15.100	64	14.453	51	13.209
Speed limit	130		71		70	

Own calculations

In a next stage, given the levels of speed and activity above, we calculate the welfare losses under the different instruments. Table 13 represents the welfare losses if people drive at their private optimal speed and of each measure for the different roads, taking into account the distribution of values of time.

Table 13 : Welfare losses (euro/driver)

Welfare losses	*Social*	*Private*	*Strict liability*	*Regulation*
Highway	0	-69	-11	-76
Interurban	0	-2.345	-182	-127
Urban	0	-2.694	-243	-222

Welfare losses	*Tax*	*Tax + Strict liability*	*Tax + Regulation*	*Regulation + Strict liability*
Highway	-64	**-10**	-72	-10
Interurban	-1.965	-169	**-92**	-167
Urban	-1.771	-213	**-92**	-248

Own calculations

If we look at the total welfare losses, we see that for the interurban and urban roads the losses are the smallest under regulation and a km tax and the highest, except for the private optimum, under a tax used alone. For the highway the losses are the smallest under a tax and strict liability[28] and the highest under regulation. Remark that the ordering of the measures depends on the assumptions made. Note that adding an instrument does not necessarily increases welfare. Regulation on its own, for example, performs better than the joint use of regulation and strict liability on interurban and urban roads.

We perform a sensitivity analysis to see how the results change under different assumptions. We find that if the level of assets, y, or the probability of conviction, q, is low[29], the results do not change. However, if the probability of conviction is one, strict liability alone is

[28] The difference between a tax + strict liability and regulation + strict liability is situated after the comma.

[29] $y = 50{,}000$ or $q = 0.1$

preferred on all road types. If the value of harm, *h*, is only half of the values of the base scenario, we again prefer the km tax and regulation on the interurban and urban roads. On the highway, strict liability is then preferred. Since diesel cars travel relatively more kilometres, we change the proportion of diesel versus gasoline cars and find again that a tax and regulation on interurban and urban roads and a tax and strict liability on highways are preferred. If there are no business people on the road, it makes sense that regulation and a km tax is preferred on all road types. The values of time are then more concentrated around the mean. If the values of time are not concentrated, for example if we have only business people and others, strict liability and a km tax will be preferred on all road types.

7. CONCLUSION

In this paper we consider three instruments to promote traffic safety: strict liability, regulation and a kilometre tax. We assume that the expected accident cost depends on the level of speed and the number of kilometres one drives. We show that in a setting of unilateral accidents in which only one party has losses government intervention is needed; otherwise people drive too fast and too much.

We start with the analysis of strict liability. We find that because of the judgement proof problem and/or because the probability of being held liable does not equal one strict liability does not work perfectly. People drive too much and too fast. Regulation does not lead to the optimal solution because the government lacks information. It sets a uniform speed limit while the optimum differs between people; hence some people drive too fast and others too slowly. The activity level is not directly influenced under regulation, hence people drive too much. The kilometre tax used alone does not control the level of speed and since it is set uniform it will not lead to the socially optimal activity level either. Joint use can perform better but will, in general, not lead to the socially optimal solution. Which instrument performs best depends on a number of factors such as the harm done, the assets of the driver, the distribution of the value of time and the performance of strict liability. We illustrated this by means of a numerical application.

In the basic analysis we assume that people comply with the regulation. This is of course not realistic. We relax this assumption and consider the optimal enforcement problem. We calculate the optimal fine, probability of detection and the speed limit. We find that the speed limit is stricter if there is no full compliance.

This is a first attempt to model traffic safety. Many extensions and improvements to the theoretical framework and the exercise are possible.

An important extension would be the incorporation of the costs of the measures. In determining the welfare losses of different measures we should not only look how ‘close’ the measure brings us to the optimum, but also at his costs. In the analysis up to now we only considered the costs of enforcement. However strict liability and a kilometre tax also have their costs. Think for example of the cost of the lawyers, courts, infrastructure,…

Another possible extension would be the inclusion of bilateral accidents; this is of accidents in which both parties influence the probability of an accident and both have losses. This would increase the realism of the model but would also make it more complicated. The behaviour of one party would depend on the behaviour of the other party and we should consider different liability rules.

Further it would be useful to consider risk averse drivers and insurance. Insurance is of particular interest since it influences the expected cost under strict liability of people.

Up to now we only looked at accidents, a further extension could exist of including other external costs such as congestion, pollution, noise,…

With respect to the empirical illustration it is clear that we could incorporate the theoretical analysis of enforcement into the exercise.

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Figure 1 : Speed level under strict liability (*q*<1)

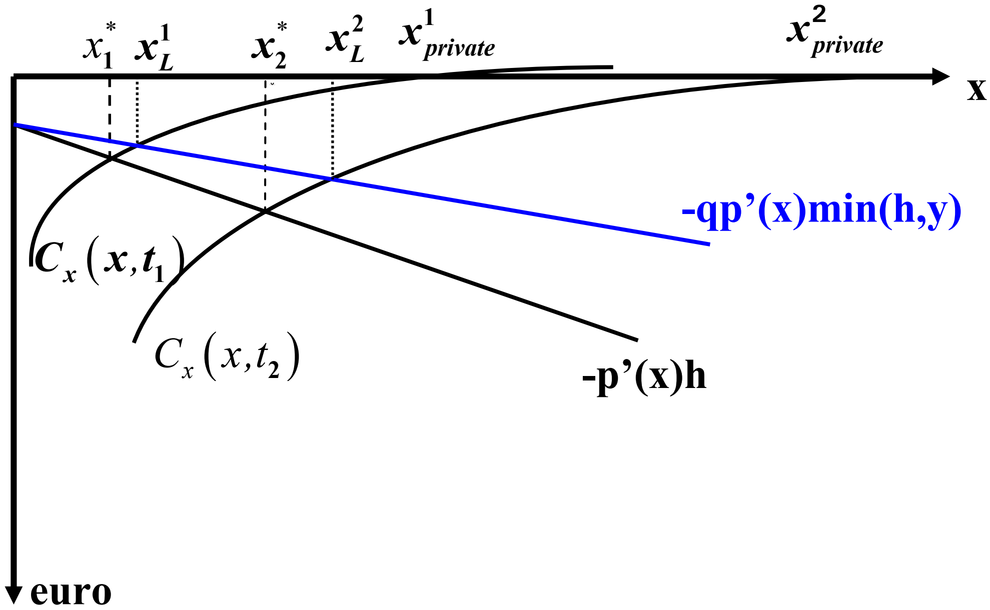


Figure 2: Activity level under strict liability

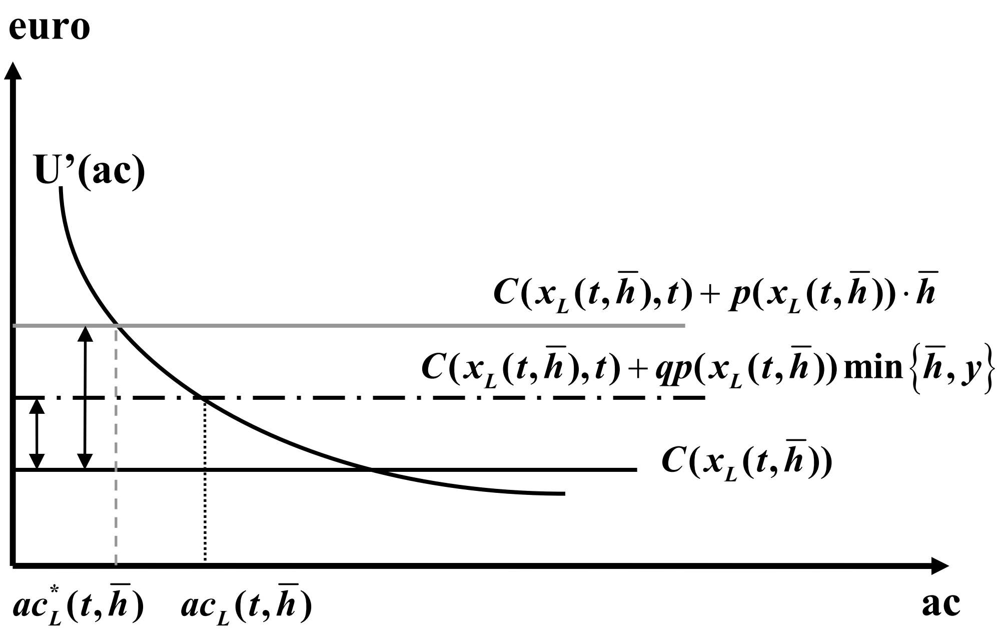


Figure 3: Speed level under regulation (1)

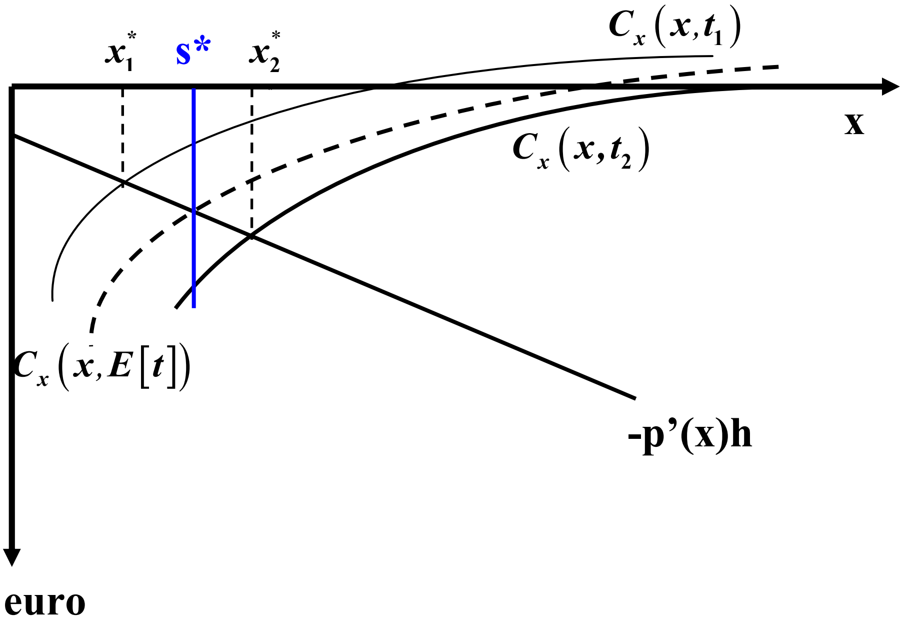


Figure 4 : Activity level under a kilometre tax

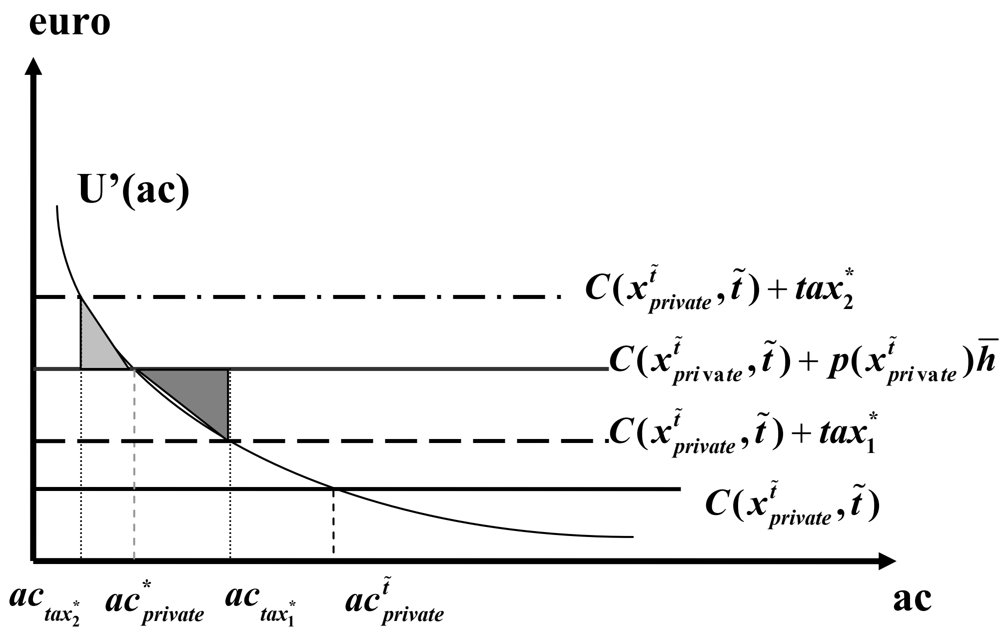


Figure 5 : Optimal fixed enforcement costs

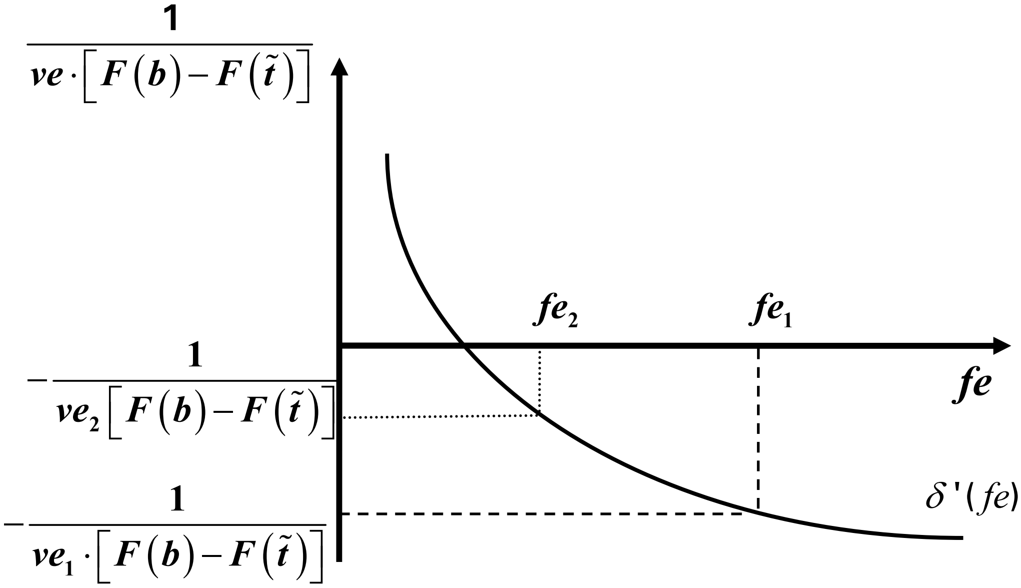
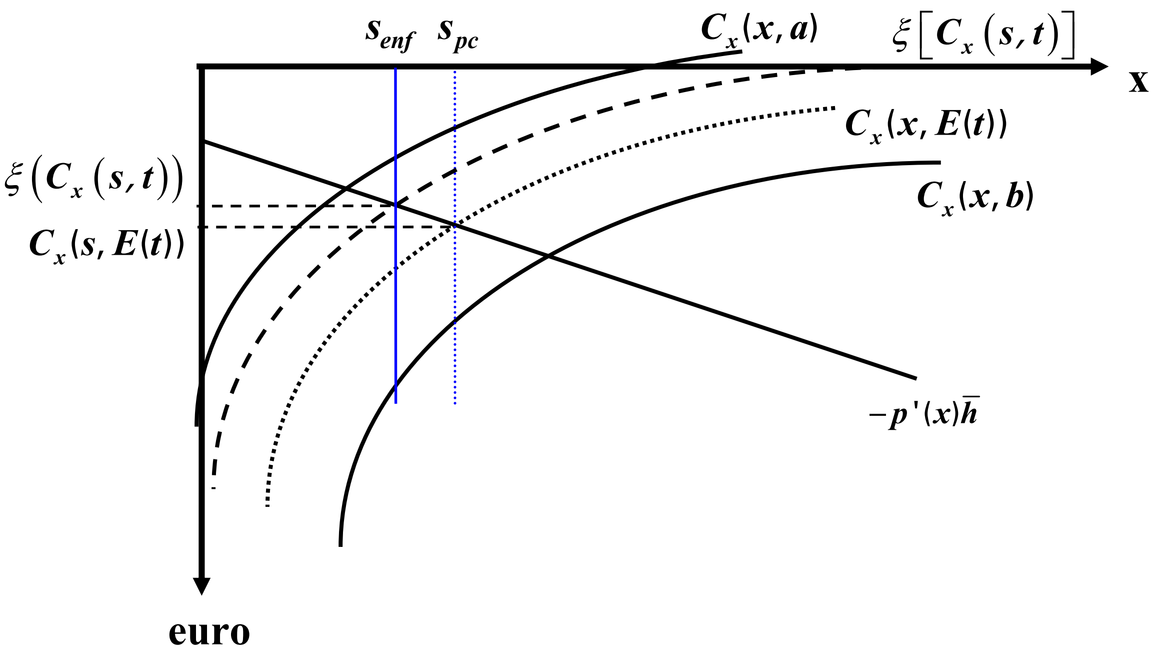


Figure 6 : Optimal speed limit under imperfect compliance



Equation Section (Next)

Appendix A : Proofs Social Optimum

a) For a given harm, $\bar{h}$, the socially optimal speed level is an increasing function of the value of time, $x_t^*(t,\bar{h})>0$.

Proof: if we differentiate (5) with respect to t, we obtain

$$\begin{aligned} & C_{xx}(x,t)\cdot x'(t)+C_{xt}(x,t)=-p''(x)\cdot\bar{h}\cdot x'(t) \\ & \Leftrightarrow C_{xt}(x,t)=\left[-p''(x)\cdot\bar{h}-C_{xx}(x,t)\right]\cdot x'(t) \\ & \Leftrightarrow x'(t)=\frac{C_{xt}(x,t)}{-p''(x)\cdot\bar{h}-C_{xx}(x,t)}>0 \end{aligned} \quad \text{(A1)}$$

given $C_{xt}<0$. ■

b) For a given value of time, $\bar{t}$, the socially optimal speed level is a decreasing function of harm, $x_h^*(\bar{t},h)<0$.

Proof: If we differentiate (5) with respect to h, we get

$$\begin{aligned} & C_{xx}(x,\bar{t})\cdot x'(h)=-p'(x)\cdot 1-p''(x)\cdot x'(h)\cdot h \\ & \Leftrightarrow p'(x)=\left[-p''(x)\cdot h-C_{xx}(x,\bar{t})\right]\cdot x'(h) \\ & \Leftrightarrow x'(h)=\frac{p'(x)}{-p''(x)\cdot h-C_{xx}(x,\bar{t})}<0 \end{aligned} \quad \text{(A2)}$$

■

c) For a given harm, $\bar{h}$, the socially optimal activity level decreases in the value of time, $ac'(t)<0$.

Proof: If we differentiate (6) with respect to the value of time, t, we obtain

$$\begin{aligned} & U''(ac)\cdot ac'(t)=C_t(x,t)+\left[p'(x)\cdot\bar{h}+C_x(x,t)\right]\cdot x'(t) \\ & \Leftrightarrow ac'(t)=\frac{C_t(x,t)+\left[p'(x)\cdot\bar{h}+C_x(x,t)\right]\cdot x'(t)}{U''(ac)}<0 \end{aligned} \quad \text{(A3)}$$

■

d) For a given value of time, $\bar{t}$, the socially optimal activity level decreases in the level of harm, $ac'(h)<0$

Proof: If we differentiate (6) with respect to the level of harm, h, we get

$$\begin{aligned} & U''(ac)\cdot ac'(h)=C_x(x,\bar{t})\cdot x'(h)+p(x)+p'(x)\cdot h\cdot x'(h) \\ & \Leftrightarrow ac'(h)=\frac{C_x(x,\bar{t})\cdot x'(h)+p(x)+p'(x)\cdot h\cdot x'(h)}{U''(ac)}<0 \end{aligned} \quad \text{(A4)}$$

■

Equation Section (Next)

Appendix B : Joint use.

(1) Regulation and strict liability

Proposition:
If the incentives under liability alone are diluted by incomplete conviction or the judgement proof problem, three cases can arise under joint use of regulation and strict liability:

a) First of all, joint use could be optimal. Under joint use the maximum level of speed, s^{**}, is higher than the level of regulation, s^*, if regulation is used alone. However it is lower than the first-best level of speed for those parties with the highest value of time, $x^*(b,\overline{h})$.

$$x^*(b,\overline{h}) > s^{**} > s^* \tag{B1}$$

Furthermore, in this case some parties are induced by liability to lower their speed more than required. A sufficient condition for (B1) to hold is

$$x_L(a,\overline{h}) < s^* \tag{B2}$$

Or equivalently, strict liability causes enough tempering of speed such that the level of speed under strict liability for the driver with the lowest value of time is lower than the speed limit. In other words, the incentive for moderating speed is not excessively diluted ($q > \tilde{q}(y)$ and $y > \tilde{y}(q)$).

b) Secondly, regulation alone could be optimal. The optimal regulatory standard then equals the optimal standard where regulation is used alone, that is

$$s^{**} = s^* \tag{B3}$$

In this case, no party will drive slower than s^{**}. This is the result if strict liability does not work well. ($q < \tilde{q}(y)$ and $y < \tilde{y}(q)$) or if the variability amongst parties is sufficiently small (distribution of t is relatively concentrated around the mean).

c) Thirdly, strict liability on its own could be optimal. In that case the standard is set equal or higher than the level of speed of the person with the highest value of time under strict liability alone, that is

$$s^{**} \geq x_L(b,\overline{h}) \tag{B4}$$

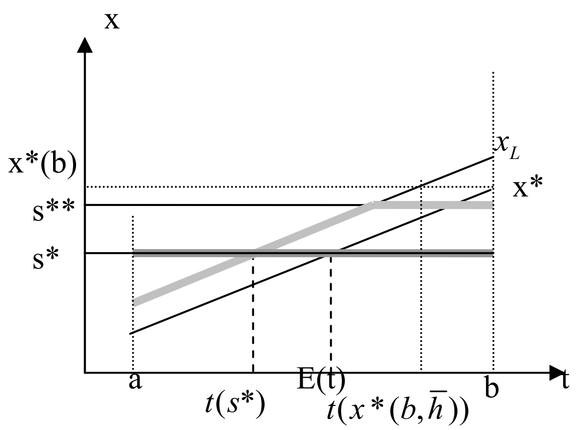
In this case, everyone will drive at his optimal level of speed under strict liability. This is the result if liability is not much diluted ($q > \tilde{\tilde{q}}(y) > \tilde{q}(y)$ and $y > \tilde{\tilde{y}}(q) > \tilde{y}(q)$) or if the variability of the values of time is large.

Proof
In this proof we focus on the level of speed since speed is directly influenced by both regulation and strict liability. The activity level is not directly influenced by the speed limit, but is mainly determined by strict liability. We already proofed that, if liability is diluted, this would lead to an excessive activity level. To make things more clear we first give an intuitive proof of the proposition and next give the formal proof.

Intuitive Proof:
(a) To understand why s^{**} may be larger than s^*, consider Figure 7 and condition (B2) $x_L(a,\overline{h}) < s^*$, which means that some parties drive more slowly than the speed limit because of liability. The reason why this condition implies $s^{**} > s^*$ is that when regulation is used

alone, increasing the standard above $s*$ was not worthwhile, because it made all parties drive faster. Here it only results in people with *t>t(s*)* driving faster; parties with a low value of time are induced to lower speed levels than $s*$ by strict liability. This means that strict liability takes up some of the welfare loss resulting from raising the maximum speed.

Figure 7: Optimal joint use: case where some parties drive slower than the speed limit



On the other hand, to understand why $s** < x*(b,\bar{h})$, suppose that $s** = x*(b,\bar{h})$. All people with $t < t(x*(b,\bar{h}))$, will drive at $x_L(t,\bar{h})$, the others will drive at $s**$. However these people, except for *t=b*, drive too fast compared to the optimum. Observe that lowering the level of speed from the level *x*(b)* does not lead to a first order change in expected social cost for people with *t=b*, but it leads to a reduction of the social cost for people with $t \geq t(x*(b,\bar{h}))$.

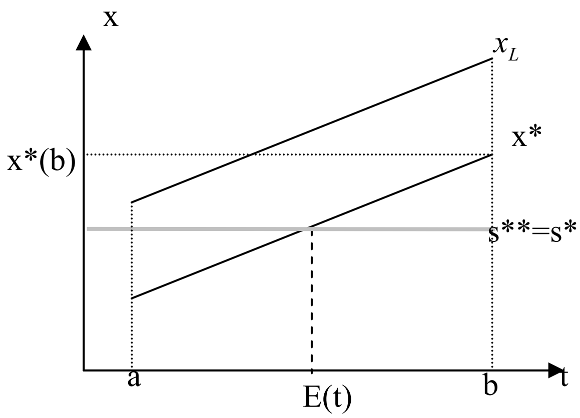
In the formal proof we will show that $s**$ is determined by

$$\left[p'(s)\bar{h} + \frac{\int_{t(s)}^{b} C_x(s,t) f(t) dt}{\int_{t(s)}^{b} f(t) dt} \right] = 0 \qquad \text{(B5)}$$

This can be interpreted as follows: the expected marginal cost of (reducing) the speed level equals the reduction in harm, where expectation is over only those parties who are not affected by strict liability and thus are affected by the maximum speed level. Note that (B5) is the analogue of (12).

(b) It is evident from Figure 8 why this case arises if the incentives created by strict liability are too much diluted: then the incentive to lower one's speed created by strict liability is too weak to take up any of the slack due to raising the speed limit above $s*$. It is therefore best to leave the standard at $s*$. This is a case in which regulation should be used alone, strict liability has nothing to add but cost. If the variability of the values of time is low, regulation will be optimal. Consider the extreme case where there is only one value of time. Regulation will then lead to the social optimum.

Figure 8: Optimal joint use: case where all parties drive at the maximum speed level.



(c) If liability works perfectly (q=1, $y \geq \bar{h}$), it is clear that regulation has nothing to add. If liability works close to perfect, it could be optimal to use it as the only instrument. If the variability of the value of time is high, it could also be optimal to use strict liability alone, since this measure takes into account the individual values of time, while regulation only looks at the average.

Formal Proof:

We first prove part a), then b) and finally c).

Proof of part a

The proof of this part consists of four steps:

In **(i)**: $s^* \leq s^{**} \leq x^*(b,\bar{h})$

In **(ii)**: if s*<s** then $x_L(a,\bar{h}) < s^{**}$

In **(iii)**: $s^{**} < x^*(b,\bar{h})$ and $\left[p'(s)\bar{h} + \frac{\int_{t(s)}^{b} C_x(s,t) f(t)dt}{\int_{t(s)}^{b} f(t)dt} \right] = 0$

In **(iv)**: if $x_L(a,\bar{h}) < s^*$ then s*<s**

(i) s** must lie between s* and $x^*(b,\bar{h})$.

It is easy to verify that for every t, the expected social costs are lower at s=$x^*(b,\bar{h})$, than at a higher speed limit. Under s=$x^*(b,\bar{h})$, all parties except people with a value of time equal to b, drive too fast. Under s>$x^*(b,\bar{h})$ even parties with a value of time equal to b drive too fast. Hence, $s^{**} \leq x^*(b,\bar{h})$.

To show that $s^* \leq s^{**}$, assume otherwise s**<s*. Let SC(s;r) be the expected social cost, when regulation is used alone and let SC(s;rl) be the expected social cost when regulation is used jointly with liability. Then for any $s_1 > s_2$, we claim that the difference in social cost when regulation is used alone is larger than the difference when they are jointly employed.

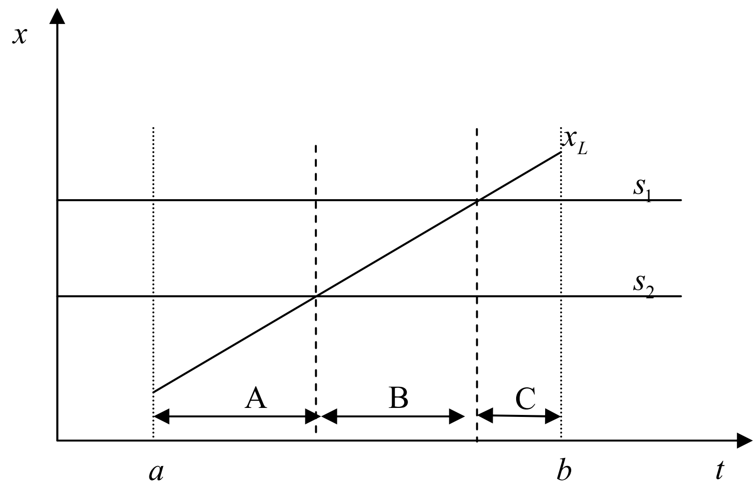
$$SC(s_1;r)-SC(s_2;r)\geq SC(s_1;rl)-SC(s_2;rl) \quad \text{(B6)}$$

This can be shown by demonstrating that the corresponding weak inequality in social costs holds for given $\overline{h}$ and every t:

$$\left[C(s_1,t)+p(s_1)\overline{h}\right]-\left[C(s_2,t)+p(s_2)\overline{h}\right]\geq$$
$$\left[C(\min\left\{s_1,x_l(t,\overline{h})\right\},t)+p(\min\left\{s_1,x_l(t,\overline{h})\right\})\overline{h}\right]-\left[C(\min\left\{s_2,x_l(t,\overline{h})\right\},t)+p(\min\left\{s_2,x_l(t,\overline{h})\right\})\overline{h}\right]$$
(B7)

We can see this on Figure 9.

Figure 9 : joint use versus regulation



The regions A,B and C show the different possible relations that may hold among s_1, s_2 and $x_L(t,\overline{h})$. For t in region C, (B7) holds with equality for the parties will act identical under regulation used alone as under joint use. For t in region B, parties will drop their level of speed from s_1 to s_2 if regulation is used alone. Under joint use, they will only drop their speed from $x_L(t,\overline{h})$ to s_2. (B7) becomes

$$\left[C\left(s_1,t\right)+p\left(s_1\right)\overline{h}\right]-\left[C\left(s_2,t\right)+p\left(s_2\right)\overline{h}\right]\geq\left[C\left(x_L(t,\overline{h}),t\right)+p\left(x_L(t,\overline{h})\right)\overline{h}\right]-\left[C\left(s_2,t\right)+p\left(s_2\right)\overline{h}\right]$$
$$\Rightarrow\left[C\left(s_1,t\right)+p\left(s_1\right)\overline{h}\right]\geq\left[C\left(x_L(t,\overline{h}),t\right)+p\left(x_L(t,\overline{h})\right)\overline{h}\right]$$

However, this holds with strict inequality since the expected social cost is convex in the level of speed and for t in region B, $s_1(t,\overline{h})>x_L(t,\overline{h})>x^*(t,\overline{h})$. In region A, (B7) also holds with strict inequality since, under regulation on its own, the level of speed drops from s_1 to s_2. Moreover, the expected social costs are convex and in for t in region A, $s_1(t,\overline{h})>s_2(t,\overline{h})>x^*(t,\overline{h})$. The expected social costs are thus lower at s_2 than at s_1. Hence, the difference is positive. Under joint use, the level of speed stays at $x_L(t,\overline{h})$; hence, the expected social costs do not change and the difference is zero. Thus, since the difference in regulation is positive and the difference in joint use is zero, the strict inequality holds.

If s*>s**, we conclude out of (B6) that

$$SC(s^*;r)-SC(s^{**};r)\geq SC(s^*;rl)-SC(s^{**};rl) \quad \text{(B8)}$$

As s** minimises SC(s;rl) over s, we know that

$$SC(s^*;rl) - SC(s^{**};rl) \geq 0 \tag{B9}$$

Hence

$$SC(s^*;r) - SC(s^{**};r) \geq 0 \tag{B10}$$

which contradicts the fact that s* is the unique minimum of minimising SC(s;r) over s. We conclude that $s^* \leq s^{**}$.

(ii) We prove that s**>s* implies that some parties will drive slower than s** due to liability, this is, $x_L(a,\bar{h}) < s^{**}$.

Suppose otherwise, $x_L(a,\bar{h}) \geq s^{**}$. Then for $s \leq s^{**}$, the second term in (24) becomes relevant. In this case, no one will be induced by liability to drive slower; hence regulation will be used on its own. The regulator will $\min\limits_{s \leq x_L(a,\bar{h})} \int_a^b \left[C(s,t) + p(s)\bar{h} \right] f(t)dt$. Since this term has a unique solution over all s at s* and since $s^* < s^{**}$, the term must have a unique minimum over $s \leq s^{**}$ at s*. However, this means that s**=s*, but this contradicts our starting point that s**>s*.

(iii) Here we prove that s**>s* implies $s^{**} < x^*(b,\bar{h})$ and that s** is determined by the first order condition (B5). This is $\left[p'(s)\bar{h} + \dfrac{\int_{t(s)}^{b} C_x(s,t) f(t)dt}{\int_{t(s)}^{b} f(t)dt} \right] = 0$

Out of **(ii)** follows that if s**>s*, the regulator will use regulation and liability jointly. Hence, the first term in expression (24) is relevant for all s in the interval properly including $x^*(a,\bar{h})$ and s**. He will

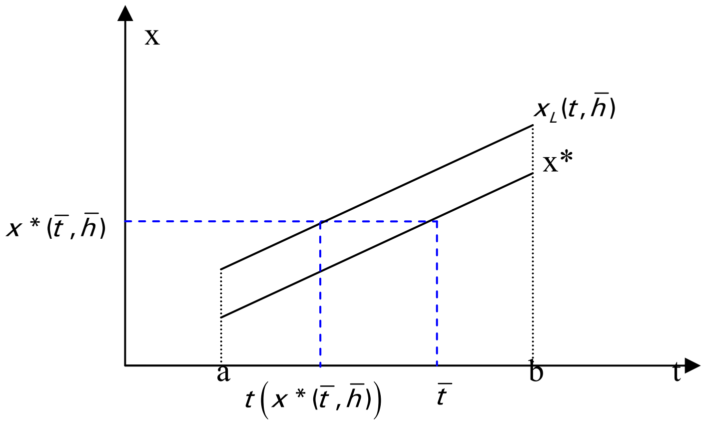
$$\min_{x_L(b,\bar{h}) > s > x_L(a,\bar{h})} \left(\int_a^{t(s)} \left[C\left(x_L(t,\bar{h}),t\right) + p\left(x_L(t,\bar{h})\right)\bar{h} \right] f(t)dt + \int_{t(s)}^{b} \left[C\left(s,t\right) + p\left(s\right)\bar{h} \right] f(t)dt \right)$$

In particular, the first derivative with respect to s, evaluated at s** should be zero. We calculate the first derivative:

$$\int_{t(s)}^{b} C_x\left(s,t\right) f(t)dt + p'(s)\bar{h} \int_{t(s)}^{b} f(t)dt \tag{B11}$$

From **(i)** we know that $s^{**} \leq x^*(b,\bar{h})$. For any t such that $x^*(t,\bar{h})$ lies in the domain of $t(\ )$, we have $t\left(x^*(t,\bar{h})\right) < t$ (see also Figure 10), hence, $t\left(x^*(b,\bar{h})\right) < b$ and since $t(\ )$ is increasing in its argument; we know that $\int_{t(s)}^{b} f(t)dt > 0$.

Figure 10



Rewriting (B11) we have

$$\int_{t(s)}^{b} f(t)dt \left[p'(s)\bar{h} + \frac{\int_{t(s)}^{b} C_x(s,t) f(t)dt}{\int_{t(s)}^{b} f(t)dt} \right] \tag{B12}$$

(B12) equals zero at s**, hence, $\left[p'(s^{**})\bar{h} + \frac{\int_{t(s)}^{b} C_x(s^{**},t) f(t)dt}{\int_{t(s)}^{b} f(t)dt} \right] = 0$.

In **(i)** we already showed that $s^{**} \leq x^*(b,\bar{h})$. To prove that $s^{**} < x^*(b,\bar{h})$, we only need to show that $s^{**} \neq x^*(b,\bar{h})$. We do this by proving that at $s^{**} = x^*(b,\bar{h})$, (B12) does not equal zero.

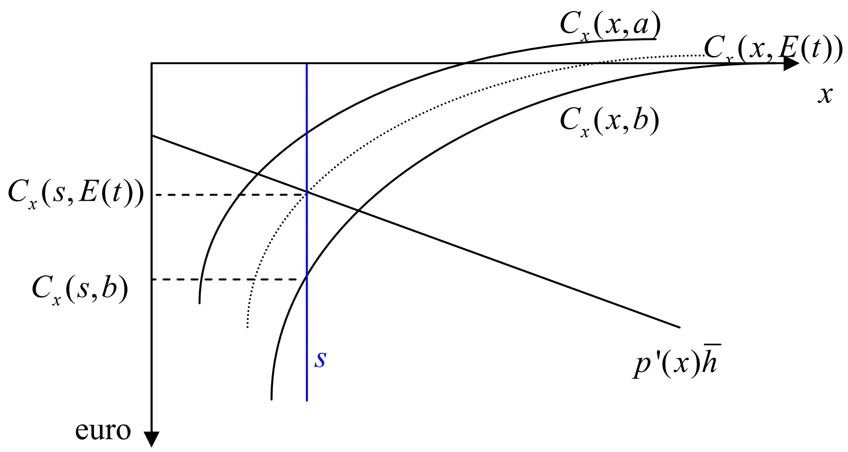
We know that $t\left(x^*(b,\bar{h})\right) < b$, hence $\int_{t\left(x^*(b,\bar{h})\right)}^{b} f(t)dt > 0$. Furthermore observe that (B13) is the mean of the derivative of the private cost, given that the value of time is in the interval [t(s),b].

$$\frac{\int_{t(s)}^{b} C_x(s,t) f(t)dt}{\int_{t(s)}^{b} f(t)dt} \tag{B13}$$

(B13) tends to the derivative of the private cost, given a value of time b, if t(s) tends to b. Given Figure 11 note that (B13) increases if t(s) increases. Thus, if $s = x^*(b,\bar{h})$, (B13) $> C_x(x^*(b,\bar{h}),b)$ since $t(x^*(b,\bar{h}))<b$. Observe that $C_x(s,t) + p'(s)\bar{h} = 0$ for $t=b$ if $s = x^*(b,\bar{h})$. Given that (B13)$> C_x(x^*(b,\bar{h}),b)$, it follows that the second term in (B12)>0.

Since the first term was also positive, it is clear that (B12)>0. Hence (B12) $\neq 0$ when evaluated at $x^*(b,\bar{h})$

Figure 11



(iv) If (B2), $x_L(a,\bar{h}) < s^{**}$ holds, s**>s*.

Suppose otherwise, $s^{**} \leq s^*$. In (i) we proved that $s^* \leq s^{**}$, hence s**=s*. However, suppose (B2) implies that the first term in (24) is relevant at s*. We need only to show that (B12)>0 at s* to contradict the presumed optimality of s**=s*. Note that from (13) and (5) that $\int_a^b C_x(s^*,t)f(t)dt + p'(s)\bar{h}\int_a^b f(t)dt = 0$. However, (B13) $< \int_a^b C_x(s^*,t)f(t)dt$, hence $\int_{t(s)}^b C_x(s^*,t)f(t)dt + p'(s)\bar{h}\int_{t(s)}^b f(t)dt > 0$

Remark that (B2) will hold if q and y are sufficiently high, for as q approaches 1 and y sufficiently large, $x_L(a,\bar{h})$ will go to $x^*(a,\bar{h}) < s^*$.

<u>Proof of part b.</u>

(v) If s** equals s*, no one will drive slower than s*.

Otherwise, if $x_L(a,\bar{h}) < s^*$, which by **(iv)** implies that s**>s*, a contradiction.

(vi) If $x_L(a,\bar{h})$ sufficiently high, then s**=s*. This is, if the incentives created by liability are so diluted that adding liability does not change the level of speed, the optimal standard equals the standard if regulation is used alone. In fact, you only use regulation, liability has nothing to add.

Assume the contrary, then it must be possible that s**>s*, for an $x_L(a,\bar{h}) \geq x^*(b,\bar{h})$. But by **(ii)** we know that if s**>s*, then $x_L(a,\bar{h}) < s^{**}$. Hence, $x^*(b,\bar{h}) \leq s^{**}$. This contradicts **(i)**, so that certainly for all $x_L(a,\bar{h})$ as high as $x^*(b,\bar{h})$, s**=s*.

Remark also that it is clear that as q decreases, so does $x_L(a,\overline{h})$ and it tends to the private optimal speed as q tends to zero. Similarly, if y tends to a. Hence if q or y sufficiently small: s**=s*.
If the variability of the values of time is low, regulation will be optimal. Consider the extreme case where there is only one value of time. Regulation will then lead to the social optimum.

Proof of part c.

(vii) $s^{**} \geq x_L(b,\overline{h})$

Assume that q=1, $y \geq \overline{h}$, then strict liability works perfectly, that is $x_L(t,\overline{h}) = x^*(a,\overline{h})$ for all t. Since the social cost function is convex and continuous, there exist a level of conviction for a given level of assets $\tilde{q}(y)$ and a level of assets $\tilde{y}(q)$ for a given level of conviction, such that strict liability on its own is preferred.
If there is sufficient variability, strict liability on its own will also be preferred, since it takes into account the variability in t, while regulation only takes into account the average value of time.

■

(2) Strict liability and a kilometre tax

Under joint use people are strictly liable if an accident happens and they pay a tax on their activity level. Hence the driver maximises his utility, taking into account his private costs, his expected liability costs and the tax.

$$\max_{ac,x} U(ac) - ac \cdot \left[C(x,t) + qp(x)\min\left\{y,\overline{h}\right\} + tax_{jl}^{*} \right] \tag{B14}$$

The first order conditions with respect to the level of speed are

$$\begin{aligned} &-ac \cdot \left[C_x(x,t) + qp'(x)\min\left\{y,\overline{h}\right\} \right] = 0 \\ &\Leftrightarrow C_x(x,t) + qp'(x)\min\left\{y,\overline{h}\right\} = 0 \end{aligned} \tag{B15}$$

This gives the same level of speed as under strict liability used alone, $x_L(t,\overline{h})$.

For the driver, the first order condition with respect to the activity level then is

$$U'(ac) = C(x_L(t,\overline{h}),t) + qp(x_L(t,\overline{h}))\min\left\{y,\overline{h}\right\} + tax_{jl}^{t} \tag{B16}$$

The government maximises the same social welfare as in (10) hence the first order condition looks like

$$U'(ac) = C\left(x_L(t,\overline{h}),t\right) + p\left(x_L(t,\overline{h})\right)\overline{h} \tag{B17}$$

Comparing (B17) and (B16), we find that a tax for each value of time and given $\overline{h}$ would equal

$$\begin{aligned} &qp\left(x_L(t,\overline{h})\right)\min\left\{y,\overline{h}\right\} + tax_{jl}^{t} = p\left(x_L(t,\overline{h})\right)\overline{h} \\ &\Rightarrow tax_{jl}^{t} = p\left(x_L(t,\overline{h})\right)\left[\overline{h} - q\min\left\{y,\overline{h}\right\}\right] \end{aligned} \tag{B18}$$

Given that the government can only set a uniform tax, the tax equals

$$tax^{*}_{jl} = E\left[p(x_L(t,\overline{h}))\left[\overline{h} - q\min\left\{ y,\overline{h} \right\} \right] \right] \tag{B19}$$

Again, this will not lead to the socially optimal solution. Substituting (B19) in (B16) gives

$$U'(ac) = C\left(x_L(t,\overline{h}),t \right) + qp(x_L(t,\overline{h}))\min\left\{ y,\overline{h} \right\} + E\left[p(x_L(t,\overline{h})) \right]\left[\overline{h} - q\min\left\{ y,\overline{h} \right\} \right]$$

$$\Rightarrow U'(ac) = C\left(x_L(t,\overline{h}),t \right) + E\left[p(x_L(t,\overline{h})) \right]\overline{h} + q\min\left\{ y,\overline{h} \right\}\left[p(x_L(t,\overline{h})) - E\left[p(x_L(t,\overline{h})) \right] \right] \tag{B20}$$

If $E\left[p(x_L(t,\overline{h})) \right] = p(x_L(t,\overline{h}))$, the driver will drive the optimal number of kilometres. If $E\left[p(x_L(t,\overline{h})) \right] > p(x_L(t,\overline{h}))$, the second term of the right-hand side of (B20) will be too large. The last term will correct this partly. If $q\min\left\{ y,\overline{h} \right\} = 1$, the activity level will be optimal, if it is larger than 1, the correction will be too large and the driver will drive too little; if it is smaller than 1, the correction will be too small and the activity level too high. The reasoning for $E\left[p(x_L(t,\overline{h})) \right] < p(x_L(t,\overline{h}))$ is analogous. In general, some people will drive too much, others too little.

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