TRAFFIC SAFETY: REGULATION, STRICT LIABILITY AND PRICING

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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 economics; Liability; Regulation; Accidents
Topic Area: C2-SIG3 Safety Analysis and Policy

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[2]. 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[3], 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[4]. 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[5] and a kilometre tax. Car drivers may be induced to drive at a reasonable speed by 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.

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[2] OECD (2002)
[3] Note that speed limits only influence traffic safety if there is no congestion.
[4] Lonero et al. (1995)
[5] Strict liability means that if A damages B, then A is liable for that damage.

We use a theoretical model of traffic accidents based on Shavell (1984a)[6] 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. We only focus on speed in the illustration. 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[7].

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[8]. 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[9]. $f(t)$ 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[10]. The harm is known to the regulator.

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

[6] 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.

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

[8] Given that we assume unilateral accidents, the own accident costs are zero in our model.

[9] 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.

[10] 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 $p(x) \cdot h = H(x) = p \cdot h(x) = p(x) \cdot h(x)$

drives[11], 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[12] 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

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

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.

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

[12] The proofs can be found in Delhaye (2003). To obtain this paper, please contact the author.

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[13]. Given an estimate for the value of a life of 1.670.000 euro[14], 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, $\bar{h}$ and for each value of time, *t*, the car driver maximise his utility taking into account the costs of driving and the expected liability costs. He will

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

This will lead to $x_L(t, \bar{h})$.

Prop 1: 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 $q \min\left\{ \bar{h}, y \right\}$. This level of speed is higher than the actual socially optimal speed given the harm $\bar{h}$:

$$x_L(t, \bar{h}) = x^*(t, q \min\left\{ \bar{h}, y \right\}) \ge x^*(t, \bar{h}) \tag{8}$$

Proof: Since (7) is identical in form to (4), it is clear that for all *t*, $x_L(t, \bar{h})$ is determined by the first equality in (8). To prove the inequality, note that we proved that $x^*(\bar{t}, h)$ is decreasing in *h*[15] and that $h \ge q \cdot \min\left\{ h, y \right\}$. ■

[13] Remember that we do not take into account the existence of insurance.
[14] UNITE (2001)
[15] The remainder of the analysis is for a given value of harm, $\bar{h}$. We only used the variation in *h* to prove proposition 1.

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 every 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, $-qp'(x)\min\{h, y\}$.

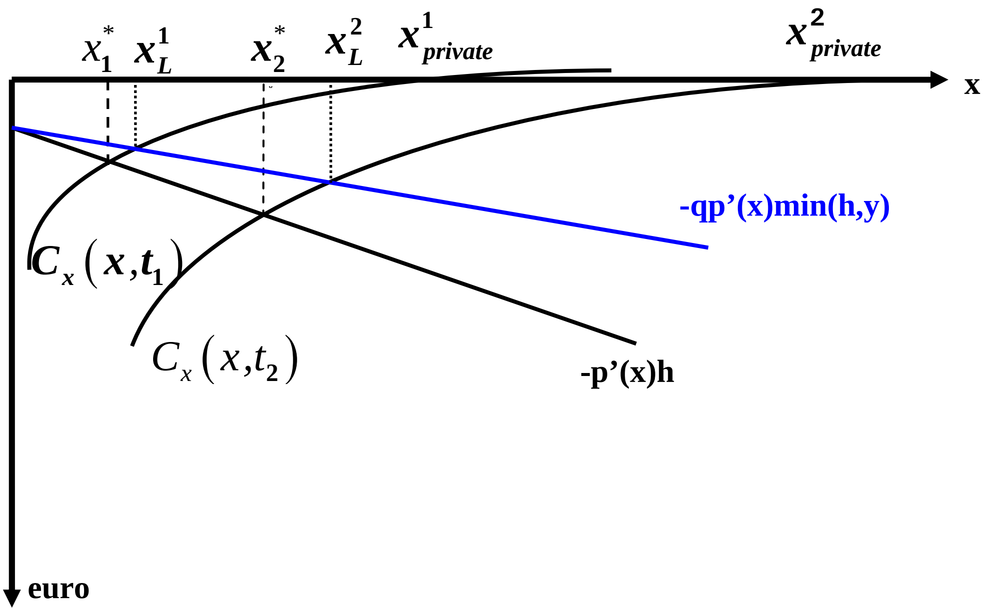

Figure 1 : Speed level under strict liability (q<1)

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, $ac_L(t,\bar{h})$ will be given by

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

The government maximises the utility taking into account the private costs and the expected accident costs.

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

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.

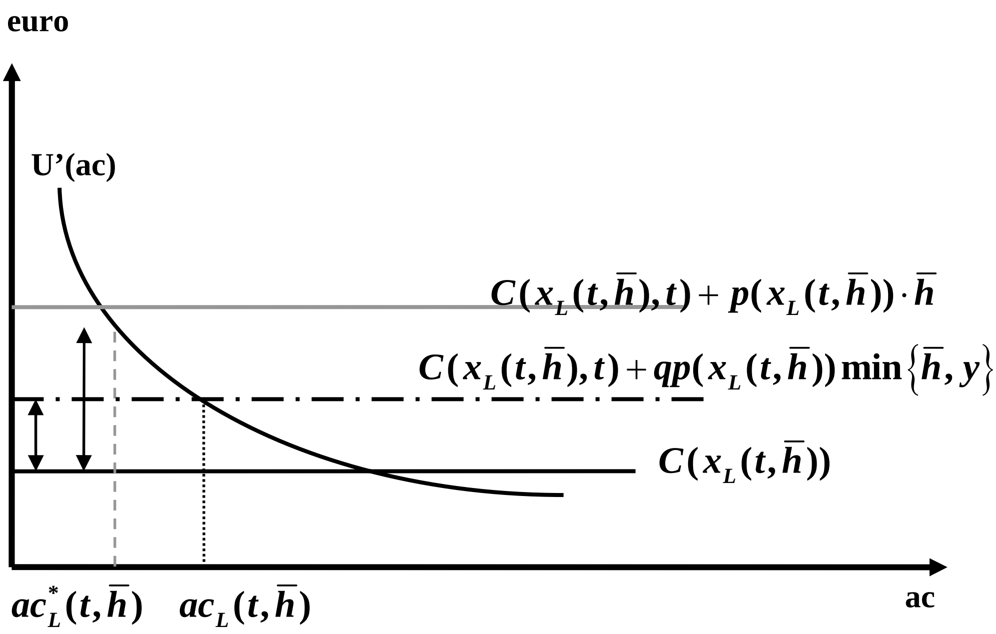

Figure 2: Activity level under strict liability

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:

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

This gives the first order condition

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

This gives s^*, the optimal regulatory standard.

Prop 2: Under regulation, for a given $\bar{h}$, the optimal standard is unique and equals the level of speed that would be first best for the party with the average value of time.

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

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

Equation (13) states that the standard will be set optimally for the person with the average value of time. 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 $t = E[t]$. 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.

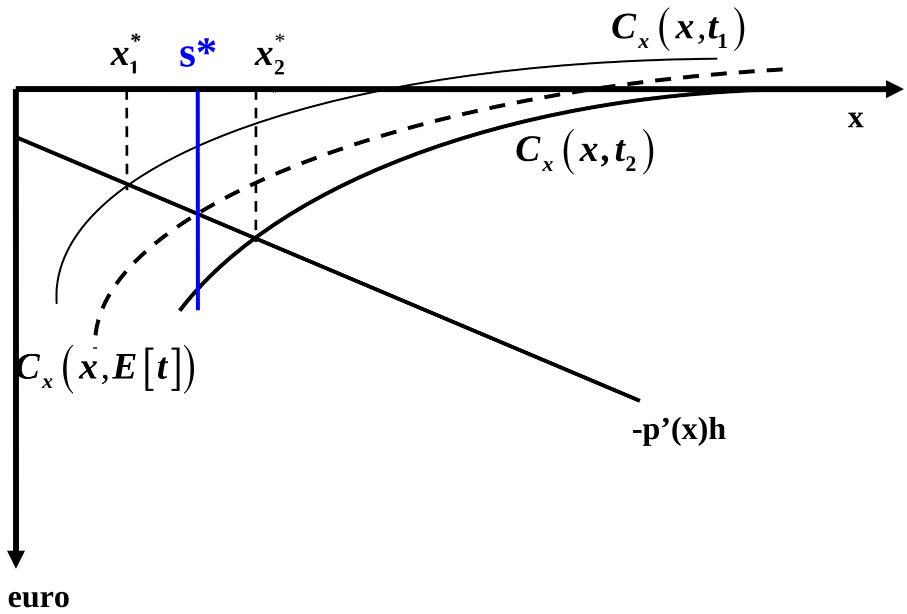

Figure 3: Speed level under regulation (1)

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.

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

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

$$U'(ac) = C(s,t) \tag{15}$$

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

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

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.

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^t_{tax} 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^t_{tax} is determined by

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

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

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

Comparing (19) and (20), it is clear that in the optimum the tax equals the external cost, $tax^*_{ac} = p\left(x^t_{private}\right)\bar{h}$. 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

$$tax^*_{ac} = E\left[p\left(x^t_{private}\right)\bar{h}\right] \tag{21}$$

The activity level for each driver is then given by

$$\begin{aligned} U'(ac) &= C(x^t_{private}, t) + tax^*_{ac} \\ &= C(x^t_{private}, t) + E\left[p\left(x^t_{private}\right)\bar{h}\right] \end{aligned} \tag{22}$$

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

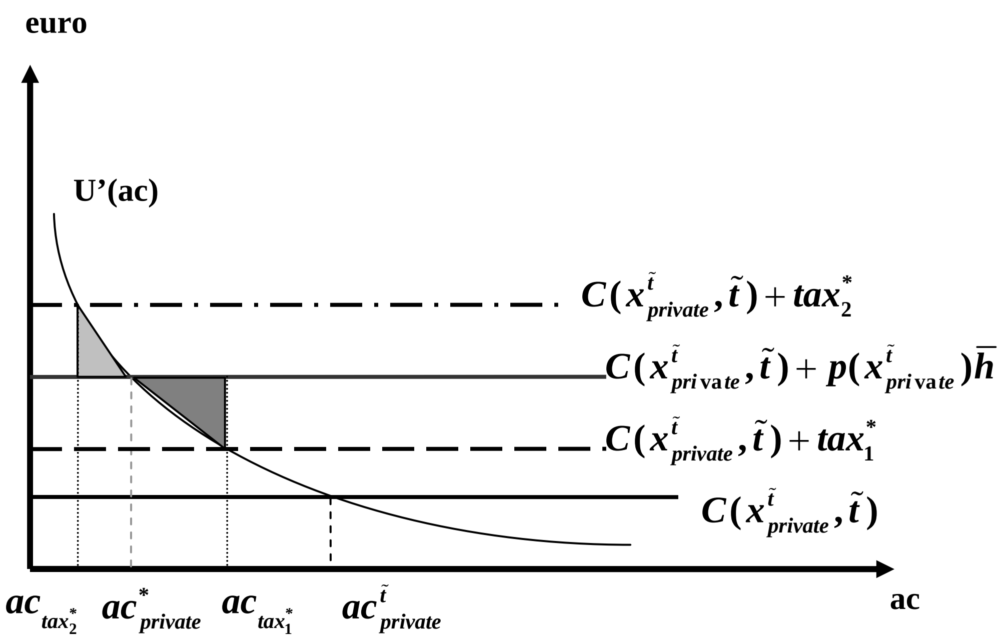

Figure 4 : Activity level under a kilometre tax

In general, the level of activity under a uniform tax will not equal $ac^*_{private}$, the socially optimal activity level given that the speed is $x^{\tilde{t}}_{private}$. 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 $\tilde{t}$ $p\left(x^{\tilde{t}}_{private}\right)\bar{h} > E\left[p\left(x^{t}_{private}\right)\bar{h}\right]$, 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 $p\left(x^{\tilde{t}}_{private}\right)\bar{h} < E\left[p\left(x^{t}_{private}\right)\bar{h}\right]$ 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 . Note that $p\left(x^{t}_{private}\right)\bar{h}$ 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 paper we mainly present the intuition. For the full mathematical derivations we refer to Delhaye (2003)

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 $\min\left\{s, x_L(t,\bar{h})\right\}$. 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 minimizes their expected cost.

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

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

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 (19) and (20) it is clear that the optimal tax under joint use equals the external cost given a speed level *s*,

$$tax_{jr}^{*} = p(s)\bar{h} \tag{24}$$

Therefore the driver will then

$$\begin{aligned} &U'(ac) = C(s,t) + tax_{jr}^{*} \\ &\Rightarrow U'(ac) = C(s,t) + p(s)\bar{h} \end{aligned} \tag{25}$$

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 the socially optimal activity level.

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.

$$\max_{ac,x} U(ac) - ac \cdot \left[C(x,t) + q \cdot p(x) \cdot \min\left\{\bar{h}, y\right\} + tax_{jl}^{*} \right] \tag{26}$$

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

$$\begin{aligned} &-ac \cdot \left[C_x(x,t) + q \cdot p'(x) \cdot \min\left\{\bar{h}, y\right\} \right] = 0 \\ &\Leftrightarrow C_x(x,t) + q \cdot p'(x) \cdot \min\left\{\bar{h}, y\right\} = 0 \end{aligned} \tag{27}$$

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

$$U'(ac) = C\left(x_L(t,\bar{h}),t\right) + qp\left(x_L(t,\bar{h})\right)\min\left\{y,\bar{h}\right\} + tax_{jl}^{t} \tag{28}$$

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

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.

Table 1.

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.

Table 1 : Overview measures

Measure		Speed	Number of kilometres
Strict liability	$q=1,\bar{h}\le y$ $q<1$ and/or $\bar{h}$	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

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 with 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

$$\varphi(x) \text{ with } \begin{cases} \varphi(x) = 0 \text{ for } x \leq s \\ \varphi(x) > 0 \text{ for } x > s \end{cases} \tag{29}$$

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

$$\begin{aligned} & C(s,t) > C(x,t) + \delta(fe)\varphi(x) \\ \Leftrightarrow\ & C(s,t) - C(x,t) > \delta(fe)\varphi(x) \end{aligned} \tag{30}$$

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.

$$\exists\tilde{t}: C(s,\tilde{t}) - C(x,\tilde{t}) = \delta(fe)\varphi(x)$$
$$\text{with}\begin{cases}\forall t \le \tilde{t}: \text{ comply with regulation}\\ \forall t > \tilde{t}: \text{ speed}\end{cases} \tag{31}$$
$$\text{and } \tilde{t} = t(\varphi(x)),\ \text{with } t'(\varphi(x)) > 0$$

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, minimizing the social costs[17] and taking into account the behaviour of the driver, this is, it will

$$\min_{\varphi(x)}\left[\underbrace{\int_a^{\tilde{t}(\varphi)}\left[C(s,t)+p(s)\bar{h}\right]f(t)dt}_{\text{comply}}+\underbrace{\int_{\tilde{t}(\varphi)}^{b}\left[C(x,t)+p(x)\bar{h}+ve\cdot\delta(fe)\right]f(t)dt+fe}_{\text{speeding}}\right] \tag{32}$$

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

$$C(s,\tilde{t}(\varphi)) - C(x,\tilde{t}(\varphi)) = (p(x)-p(s))\bar{h} + ve\cdot\delta(fe) \tag{33}$$

Substituting (31) in (33), we obtain

$$\begin{aligned}&\delta(fe)\cdot\varphi(x) = (p(x)-p(s))\bar{h} + ve\cdot\delta(fe)\\ &\Leftrightarrow \varphi(x) = \frac{(p(x)-p(s))\bar{h}}{\delta(fe)} + ve\end{aligned} \tag{34}$$

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

$$\begin{aligned}&C(s,\tilde{t}) = C(x,\tilde{t}) + \delta(fe)\varphi(x)\\ &\Rightarrow C(s,\tilde{t}) = C(x,\tilde{t}) + p(x)\bar{h} - p(s)\bar{h} + \delta(fe)\cdot ve\\ &\Rightarrow C(s,\tilde{t}) + p(s)\bar{h} = C(x,\tilde{t}) + p(x)\bar{h} + \delta(fe)\cdot ve\end{aligned} \tag{35}$$

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

$$C(s,t) + p(s)\bar{h} > C(x,t) + p(x)\bar{h} + \delta(fe)\cdot ve \tag{36}$$

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

$$C(s,E[t]) + p(s)\bar{h} = C(x,E(t)) + p(x)\bar{h} \tag{37}$$

Comparing (37) and (35) it is clear that $\tilde{t} > E[t]$. Hence the people that speed $(t > \tilde{t} > E[t])$ are people that had to drive too slowly under regulation with perfect compliance.

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

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.

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

$$\Rightarrow ve\cdot\delta'(fe)\int_{\tilde t}^{b}f(t)\,dt=-1 \qquad (38)$$

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

(38) 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 . 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.

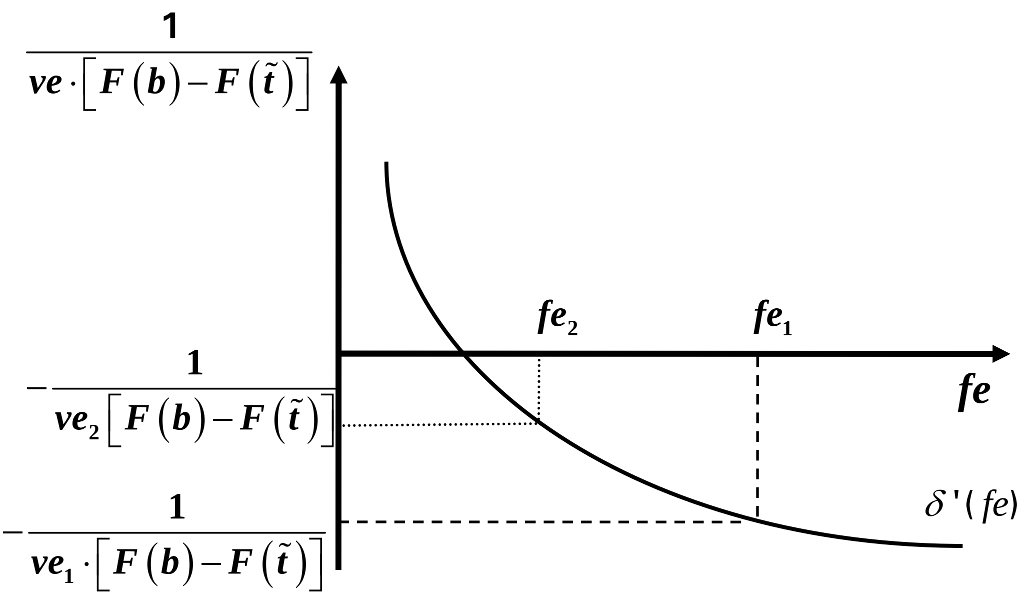

Figure 5 : Optimal fixed enforcement costs

In 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 (38) 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. Minimizing the social cost with respect to the speed limit, *s*, leads to the following first order condition

$$
\begin{aligned}
&\min_s \left[\int_a^{\tilde t} \left[C(s,t) + p(s)\bar h \right] f(t)\,dt + \int_{\tilde t}^{b} \left[C(x,t) + p(x)\bar h + ve \cdot \delta(fe) \right] f(t)\,dt + fe \right] \\
&\Rightarrow \int_a^{\tilde t} \left[C_s(s,t)\, f(t)\,dt \right] + p'(s)\bar h \int_a^{\tilde t} f(t)\,dt = 0 \\
&\Rightarrow \int_a^{\tilde t} f(t)\,dt \left[p'(s)\bar h + \frac{\int_a^{\tilde t} \left[C_s(s,t)\, f(t)\,dt \right]}{\int_a^{\tilde t} f(t)\,dt} \right] = 0 \qquad (39) \\
&\Rightarrow p'(s)\bar h + \frac{\int_a^{\tilde t} \left[C_s(s,t)\, f(t)\,dt \right]}{\int_a^{\tilde t} f(t)\,dt} = 0
\end{aligned}
$$

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 Numerical illustration

We illustrate the model with a numerical example. We only focus on speed in the illustration. We consider three types of roads; this is urban roads, interurban roads and highways. Using GAMS, we calculate the private and socially optimal levels of speed and the levels of speed under the different instruments. The results of this exercise for interurban roads are given in Table 2. More information on the exercise and the results for the other types of roads can be found in Delhaye (2003)

We first calculate the private optimal speed by minimizing the private cost with respect to the level of speed. The private cost per kilometre 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. The time cost equals the value of time divided by the level of speed. We consider three values of time corresponding with three types of persons, namely commuters $\left(t_c = € \ 6.90\right)$, businessmen $\left(t_b = € \ 23.87\right)$ and others $\left(t_o = € \ 4.75\right)$. The private optimum can be found in the first column in Table 2; we find that the levels of speed are increasing in the value of time.

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 $\left[a, \tilde t\right]$.

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. We only focus on speed in the illustration. We consider three types of roads; this is urban roads, interurban roads and highways. Using GAMS, we calculate the private and socially optimal levels of speed and the levels of speed under the different instruments. The results of this exercise for interurban roads are given in Table 2. More information on the exercise and the results for the other types of roads can be found in Delhaye (2003)

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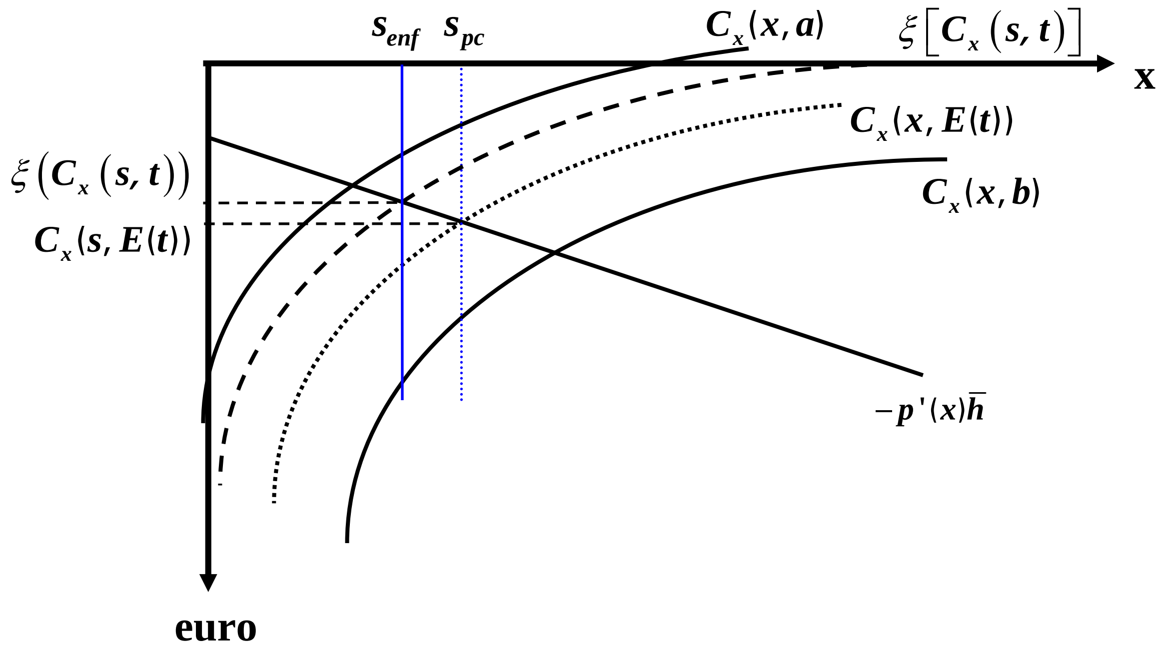

Figure 6 : Optimal speed limit under imperfect compliance

We also calculate the socially optimal levels of speed by minimizing the sum of the private cost and the expected accident cost. The expected accident cost equals the harm times the accident risk. The harm depends on the severity of the accident. We consider three types[19] of accidents, accidents with only lightly injured; accidents with severely

[18] own calculations based on Gunn et al (1997)

[19] For the moment, we do not take into account accidents with only material damage. The accident costs are based on Schwab et al (1995)

injured and fatal accidents. The accident risk[20] 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 risks per km, taking into account the influence of speed on the accident risk[21]. As predicted the social level of speed is increasing in the value of time and smaller than the private optimal levels of speed. 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[22]. Given that strict liability is diluted, the levels of speed under liability are higher than the socially optimal levels of speed but lower than the private optimal levels. We also calculate the level of regulation. The speed limits listed in Table 2 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[23] the socially optimal solution for the commuters. Hence, in the welfare analysis the losses under regulation for the commuters are zero. 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. Finally, we calculate the standard under joint use of strict liability and regulation. We find that the result is the same as if regulation is used alone.

In a next stage, given the levels of speed above, we calculate the welfare losses under the different instruments. In last row of Table 2 we represent 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 (6% are businessmen, 23% are commuters and 71% are others[24]).

Table 2 : Numerical illustration – interurban roads

	Private optimum	Social optimum	Strict liability	Regulation	Regulation + strict liability
Commuter	100	39	62	39	39
Business	144	52	86	39	39
Other	91	36	56	39	39
Welfare losses /driver/trip	1.146		0.121	0.005	0.005

Own calculations

If we look at the total welfare losses, we see that they are the smallest under regulation used alone. This corresponds with the solution under joint use, where it was already clear that regulation alone was optimal. Remark that the ordering of the measures depends on the assumptions made.

We perform a sensitivity analysis to see how the results change under different assumptions. In the base case we assumed that $y = 100,000$ and $q = 0.8$. We find that if

[20] BIVV (2000)

[21] Elvik (2000) provides a function which gives the effect of a change in speed on the accident risk:

$$\text{effect on accident risk} = 1-\left(\frac{\text{speed}}{\text{current speed}}\right)^{pr}$$ with *pr* equal to 4 for fatal accidents, 3 for accidents with serious injuries, and 2 for accidents with light injuries.

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

[23] The differences are situated after the comma.

[24] 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).

the level of assets, y, or the probability of conviction, q, is low[25], regulation is preferred. However, even if the probability of conviction is one, because of the judgement proof problem, we still prefer regulation. If the level of assets, y, is 2.000.000 euro or if the value of harm, h, is only half of the values of the base scenario, we prefer strict liability. If there are no business people on the road, it makes sense that regulation is preferred. The values of time are then more concentrated around the mean. We would expect that if the values of time are not concentrated, for example we have only business people and others that strict liability would be preferred. This is not the case. However, remember that strict liability does not work well. If we assume simultaneously that there are no commuters and that the assets equal 2.000.000 euro we see that joint use of regulation and strict liability is. Since diesel cars travel relatively more kilometres, we change the proportion of diesel versus gasoline cars and find that strict liability is preferred.

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 should look at both the welfare losses with respect to the level of speed and with respect to the level of activity.

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.

In the numerical application we calculate the welfare losses if the government does not intervene, if it uses regulation, strict liability or both. Note that we assume that the activity level is constant. Given our assumptions we find that regulation used alone is optimal. To test the robustness of our assumptions we perform a sensitivity analysis. Crucial factors are the probability of conviction, the assets versus the harm and the variability of the values of time.

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

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

only considered the costs of enforcement. However strict liability and a kilometre tax also has his 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 should incorporate accidents with only material damage, the activity level and the kilometre tax. We could also incorporate the theoretical analysis of enforcement into the exercise.

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