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INSIGHTS INTO ROAD SAFETY ENFORCEMENT

Sandra Rousseau* and Thomas Blondiau**

Abstract

In this overview we focus on the effectiveness of different road enforcement actions. After establishing the relationship between road user behavior and road safety, we concentrate on speeding, drinking and driving, and seat belt use. Then, we look at compliance enhancement policies, including engineering approaches, informational campaigns, regulation and enforcement. Finally, different monitoring and sanctioning strategies are discussed in terms of their effectiveness in reducing accident risk on roads. Overall, a single enforcement measure is shown to be insufficient to substantially reduce accident risk in the long term. Enforcement strategies combining several compliance enhancing policies are generally more effective.

Keywords: policy effectiveness; road enforcement; traffic regulation

JEL codes: K42 Illegal behavior and the enforcement of law; R Transportation economics

I. INTRODUCTION

All over the world, road traffic crashes are responsible for a substantial share in accidental deaths. Within Europe (EU 27) some 39000 people lost their lives in road accidents in 2008.[1] Traffic violations such as speeding and driving while under the influence of alcohol are generally acknowledged as important contributing factors to crash risks. Hence the importance of developing effective road traffic enforcement strategies.

Enforcement strategies typically consist of monitoring activities and sanctioning policies (e.g. Polinsky and Shavell, 2000). In general, the literature on enforcement has advised the use of targeting specific groups to maximize deterrence when enforcement budgets are limited (e.g. Harrington, 1988). However, targeting or state-dependent enforcement is not straightforward to implement in road traffic enforcement. It is often not possible to (quickly)

* KU Leuven, campus Brussel, Center for Research on Economic Markets and their Environments, Warmoesberg 26, 1000 Brussels, Belgium. Tel. +32 2 609 82 75. E-mail: sandra.rousseau@kuleuven.be.

** Idea Consult, Kunstlaan 1-2, bus 16, 1210 Brussel. E-mail: thomas.blondiau@ideaconsult.be

1 Http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Road_safety_statistics_at_regional_level.

distinguish high risk drivers from low risk drivers and to develop different monitoring strategies for those groups. As a case in point, fixed speed cameras impose the same detection probability on all passing drivers. On the other hand, for offenses such as drunk driving, it might be possible to increase monitoring probabilities for high risk drivers compared to low risk drivers by increasing the number of evening and night time inspections, especially during weekends. Thus road traffic enforcement poses its own specific challenges compared to, for example, enforcement of environmental policy (e.g. Cohen, 2000) or occupational safety enforcement (e.g. Pouliakas and Theodossiou, 2013).

In this literature review, we use a formal model of non-compliance in order to structure the multitude of research papers on road traffic enforcement. Using the critical elements of an effective enforcement strategy determined in this conceptual model, we give an outline of recent research related to road safety compliance enhancement. In doing so, we provide a (partial) update of the study of Zaal (1994). Zaal (1994) provided an extensive overview of research papers related to traffic safety enforcement. More specifically, the study focused on the enforcement of alcohol-impaired motorists, of speeding motorists, of seat belt wearing and of signalized intersections. The different types of traffic enforcement methods were described and analyzed in terms of efficiency and effectiveness. His main conclusion centered on the importance of educational and engineering approaches as well as publicity campaigns to complement road enforcement actions. In this contribution, we take a more limited approach than the one used by Zaal (1994): we concentrate on three types of violations (speeding, driving under influence and seat belt use) and we focus on the effectiveness of enforcement policies. In order to further structure the discussion, we categorize the relevant papers in terms of the type of policy instrument used for compliance enhancement.

In section 2, we start by providing a simple conceptual framework to provide structure to the literature we discuss. In section 3, we study the relationship between road user behavior and road safety. We concentrate on speeding, drinking and driving, and seat belt use. In section 4, we look at compliance enhancement policies such as engineering approaches, informational campaigns, regulation and enforcement. In section 5, different monitoring and sanctioning strategies are discussed in terms of their effectiveness in reducing accident risk on roads.

II. A SIMPLE CONCEPTUAL FRAMEWORK

In order to link different aspects of road safety enforcement we formulate a simple conceptual model. The model elements are fully in line with basic economic models of non-compliance such as those developed by Becker (1968) and Polinsky and Shavell (2000). However, in this section we explicitly apply this economic approach to road safety compliance enhancement. Previous studies have followed a more schematic and descriptive approach in creating a traffic law compliance model: for example, both the study by Mäkinen et al. (2003) and that by the European Transport Safety Council (ETSC, 2011) used a graphical scheme to present

the different forces driving compliance, while Zaal (1994) used a verbal description of the contributing factors. Earlier, Solomon (1988) specified the three E's of traffic calming as three ways that can be used to achieve adherence to traffic laws: engineering, education and enforcement. This concept of 3E's has since been the dominant approach in traffic engineering. A notable exception is the formal model used by Bjornskau and Elvik (1992) to investigate the impact of formal enforcement (monitoring and sanctioning) on speed compliance. However, their model did not include other approaches to enhance compliance such as regulation or engineering solutions. Thus the formal approach we present here constitutes a contribution to the traffic safety literature. Moreover, the model is a useful tool to structure the many studies on road traffic enforcement in a systematic way. We use a two-step approach: firstly, we look at the different determinants of driver behavior, and secondly, we discuss the regulator's policy objectives and available policy instruments.

A. DRIVER BEHAVIOR

Drivers can take several actions to improve road safety and reduce accident risks. These actions include, among other things, defensive driving, avoiding drinking and driving, wearing seat belts and not driving while fatigued. However, these preventive measures (PREV) typically come at a cost (C) which can be monetary, but can also include a loss of time or comfort. Besides these costs, drivers also take the potential reduction in their perceived private accident risk (AR_{priv}) and the reduction in the expected sanction (p_sS) for violating traffic regulation associated with these preventive actions into account. Thus drivers are assumed to minimize all private costs (accident risk, expected sanction and prevention costs) associated with particular traffic regulations by selecting the optimal amount of preventive measures (PREV). This can be modeled as:

$$\min_{PREV} AR_{priv}(PREV,INFRA,VEH,INFO) + p_sS(PREV,REG) + C(PREV)$$

In keeping with Zaal (1994), Mäkinen et al. (2003) and many other studies, we assume that the perceived private accident risk is a function of the preventive actions taken by the driver (PREV), the road infrastructure (INFRA), the technical characteristics of the vehicle (VEH) and the information available to drivers (INFO). The expected sanction is the product of the probability of receiving a sanction (p_s) and the level of the sanction (S) which depends on the level of preventive actions taken by the driver (PREV) and the regulation in place (REG).

An increase in preventive actions by the driver decreases his private accident risk and his expected sanction, but increases the costs of prevention. For this reason, the private optimal level of prevention (PREV°) is implicitly defined by the following equation:

$$\frac{dAR}{dPREV}(PREV°) + p_s\frac{dS}{dPREV}(PREV°) = -\frac{dC}{dPREV}(PREV°)$$

B. REGULATORY ACTION

Since drivers do not automatically take the necessary preventive actions, the regulator might want to influence driver behavior in order to minimize total accident risks (AR_{tot}). In most settings, the regulator will have to formulate a policy while being constrained by limited budget B. In other words, this budget constraint represents the opportunity costs of using government funds. To achieve its objective, the regulator can then choose between several policy options namely improving infrastructure (INFRA), changing vehicle characteristics (VEH), information campaigns (INFO), regulation (REG), monitoring (p_s) and enforcement (S). Thus the problem faced by the regulator can be formulated as follows:

$$\min_{INFRA,\, VEH,\, INFO, REG,\, p_s,\, S} \quad AR_{tot}\left(PREV, INFRA, VEH, INFO, REG, p_s, S\right)$$

$$s.t. \quad K\left(INFRA, VEH, INFO, REG, p_s, S\right) \leq B$$

The policy costs associated with the different policy options are represented by the function *K(.)* and these costs cannot exceed the available budget. When an internal solution is feasible, the regulator will select a level for each of the available options that lead to an equilibrium where the relative marginal impact on the accident risk compared to the marginal increase in policy costs of an increase in each of the measures is equal.

In the remainder of this text we study the different elements of this policy problem in more detail. In section 3, we describe the relationship between road user behavior (PREV) and accident risk (AR_{priv}, AR_{tot}) in more detail, especially for speeding, drinking and driving, and seat belt use. In section 4, we focus on the instruments available to the regulator in order to stimulate the adoption of preventive measures by drivers. Section 4.1 discusses engineering and technical approaches (INFRA and VEH), while section 4.2 describes informational campaigns (INFO). Regulation approaches (REG) are studied in section 4.3 and finally section 4.4 describes monitoring and sanctioning options (p_s and S). To end the literature overview, the effectiveness of these different policy measures to reduce accident risks is discussed in section 5.

III. ROAD USER BEHAVIOR AND ROAD SAFETY

While different factors, such as vehicle mechanical problems and bad weather, contribute to vehicle crashes, road user behavior has been highlighted as the key contributor to road accidents (see, for instance, Biswas et al., 2006; Fernandes et al., 2010). Many people engage in driving behavior that is intentionally or unintentionally risky. Risky driving has been consistently recognized as a prominent cause in road crashes, and many studies have observed a link between several types of risky driving behavior and road crashes (see, e.g., Iversen, 2004), particularly for younger drivers (see, e.g., Turner et al., 2004). Based on an extensive literature

overview, Petridou and Moustaki (2000) have classified the behavioral factors that jointly represent the principal cause of three out of five road traffic crashes and contribute to the causation of most of the remaining crashes. The authors distinguish four categories, namely:

- factors that reduce capability on a long-term basis: e.g., inexperience, disease, aging…,
- factors that reduce capability on a short-term basis: e.g., fatigue, acute alcohol intoxication, temporary distraction, acute psychological stress…,
- factors that promote risk taking behavior with long-term impact: e.g., habitual speeding, overestimation of own capabilities, non-use of a seat belt…, and
- factors that promote risk taking behavior with short-term impact: e.g., motor vehicle crime, psychotropic drugs use, suicidal behavior…

We illustrate the impact of risky driving-related behaviors in terms of their contribution to road crashes with some numbers of Fernandes et al. (2010). These authors mention that, of all fatal crashes that occurred in New South Wales (Australia) in 2006, 40% involved speeding, 25% involved alcohol, and at least 18% involved driver fatigue. Moreover, at least 16% of fatally-injured motor vehicle occupants were not wearing available seat belts.

In the following sections we investigate speeding, drinking and driving, and seat belt use in more detail. We do not discuss driver fatigue since the possible role of enforcement is less clear in that case, with the possible exception of the follow-up of resting times of truck and bus drivers (see, for instance, Baas et al., 2000). Thus we are able to shed more light on the relationship between road user behavior (PREV) and accident risk (AR_{priv}, AR_{tot}).

A. SPEEDING

Speeding is an important determinant of the extent of the damages associated with traffic accidents. Empirical studies show that speed not only increases the severity of a crash, but also leads to a higher probability of being involved in crashes (e.g. Elvik et al. 2004, Aarts and Van Schagen, 2006). Moreover, the relationship between speed and crash rates can be approximated by an exponential function, and that crash probabilities increase faster on minor roads than on major roads (e.g., Aarts and Van Schagen, 2006). Further, crash rates are also influenced by speed dispersion: larger differences in speed between vehicles lead to higher crash rates. In general, an acceptable representation of reality is thought to be a u-shaped relationship between driving speeds and crash involvement, where vehicles traveling significantly faster or slower than the average travel speed are more likely to be involved in a crash (see, e.g., Elvik et al., 2004; Son et al., 2009). Given the important impact of speed on accident risk and severity, it is worrying that so many drivers regularly drive too fast. For instance, the report of the ETSC (2011) mentions that the percentage of drivers of cars and vans exceeding the speed limit on rural roads ranges from lower than 30% in the Czech Republic, Austria, France and Switzerland to over 70% in Denmark and Poland.

We now look at the relation between speeding and accident risk, and note that drivers' previous speeding history can act as a predictor of accidents. For instance, Gebers (1990) argued that not only prior accidents, but also prior convictions for speeding are positively correlated with subsequent accident risk. The increase in accident risk was shown to be fairly linear. In a later study, Gebers and Peck (2003) argued that points assigned to violations and accidents in the California department negligent operator point system (US) could be used to predict which drivers are likely to be involved in future traffic accidents. Further, predictions of accident risks were shown to be dependent on the age of the driver. For instance, Daigneault et al. (2002) found that prior convictions can provide information about subsequent accidents, but that prior accidents were generally more informative for drivers over the age of 65.

B. DRINKING AND DRIVING

The concept of 'drinking and driving' can be found under several different captions in legislation and in literature. For instance, depending on regional and temporal differences, the terms 'drink driving', 'drunk driving', 'alcohol impaired driving', 'alcohol involved driving', 'driving while intoxicated' (DWI) or 'driving under the influence' (DUI) are used. Alcohol impairment is generally regarded to be the single most important cause of traffic crashes, particularly fatal crashes (e.g., Mäkinen et al. 2003; Peck et al., 2008). Given this observation, it is unfortunate that many drivers are still found to be under influence of alcohol. While less than 2% of journeys are thought to be made under in the influence of alcohol, the European Commission still estimated that at least 25% of all road deaths are alcohol related in the EU (ETSC, 2011).

Over the past decades, numerous studies have investigated the relation between drinking and crash risks. One of the earliest studies was done by Allsop (1966) who found that accident risk was significantly higher for drivers with blood alcohol levels of 80 mg/100 ml and above than for those with blood alcohol levels lower than 10 mg/100 ml. Zylman (1973) found that the relative crash risk of drivers with positive alcohol levels was 2.2 times that of sober drivers. More recently, Levitt and Porter (2001) analyzed the risks posed by drink driving and found that drivers with alcohol in their blood are seven times more likely to cause a fatal crash, whereas legally drunk drivers (i.e. drivers with an blood alcohol content (BAC) of more than 0.10 percent) pose a thirteen times greater risk than sober drivers. To obtain these results, the researchers deduced information about the composition of the driving population (drunk versus sober) by looking at the number of sober/drunk drivers involved in a two-car accident. This way, it was possible to decompose the causes of drunk driving accidents into the population composition effect and the additional traffic safety risk posed per drunk driver. Using the same case-control evaluation, Blomberg et al. (2005) found that total crash risk begins to increase significantly at BACs of 0.04–0.05 and that the increase becomes dramatic at BACs beyond 0.15. The study even reported a 120-fold increase in crash risk at BACs above

0.195 compared to drivers with a BAC of zero. Finally, the effects of BAC and age seem to interact. Using the data collected by Blomberg et al. (2005), Peck et al. (2008) showed that positive BACs in drivers under 21 were associated with higher relative accident risks than would be predicted based on an additive effect from BAC and age.

Overall, the studies show that accident risks significantly increase when drivers have been drinking. However, various studies differ with respect to the magnitude and functional form of the effect. Part of these differences might be explained by country-specific or time-specific factors, as well as the increasing complexity, and sensitivity, of the econometric techniques used to evaluate the available data.

C. SEAT BELT USE

Seat belts are the single most effective means of reducing deaths in motor vehicle crashes, with estimates of effectiveness ranging from 45 to 60% (e.g., National Highway Traffic Safety Administration, 2002; Daniels et al., 2004). Even though most people, including non-users, respond in surveys that they think belts are effective in reducing injury and that using belts is advisable (Williams and Wells, 2004), seat belt use is still far from perfect. For example, seat belt use in light vehicles is estimated to be 88% for front seats and 72% for rear seats in the EU (ETSC, 2011). Generally, increasing seat belt use is not so much a matter of convincing people that seat belts work, but of convincing them that they may actually be in an accident in which belts will be needed to protect them, or, as an inferior alternative, that they can expect a stringent penalty when caught driving without seat belt.

IV. COMPLIANCE ENHANCEMENT POLICIES

In the previous section, we described the relationship between road user behavior (PREV) and accident risk (AR_{priv}, AR_{tot}) in more detail. In the current section, we focus on the instruments available to the regulator in order to stimulate the adoption of preventive measures by drivers. This information helps in determining the relative reduction in accident risks when using a particular measure in practice and is crucial in determining optimal traffic safety regulation (see section 2). Section 4.1 discusses engineering and technical approaches (INFRA and VEH), while section 4.2 describes informational campaigns (INFO). Regulation approaches (REG) are studied in section 4.3 and finally section 4.4 describes monitoring and sanctioning options (p_s and S). As a rule, we attempt to categorize the relevant studies according to the type of policy instrument used for compliance enhancement. In the corresponding sections, we also briefly discuss the empirical results regarding the effectiveness of first three categories of measures, namely the engineering approach, the informational campaigns and the regulatory approach. The effectiveness of monitoring and sanctioning actions is discussed separately in section 5 since this constitutes the main focus of this paper.

A. TECHNOLOGICAL AND ENGINEERING APPROACH

One way to improve compliance with road safety regulation, such as speed and alcohol limits, is to make it technically difficult or even impossible, to violate the regulation. These technical solutions can include change to vehicles (VEH) as well as changes to road infrastructure (INFRA). The first category of technical measures related to vehicles include alcohol ignition interlock systems (e.g., Willis et al., 2004; Elder et al., 2011), in-car speed limiters or intelligent speed adaptation systems (e.g., Varhelyi and Mäkinen, 2001; van der Pas et al., 2012), seat belt reminder systems (e.g., Lie et al., 2008), as well as vehicle-to-vehicle wireless communication systems (e.g., Biswas et al., 2006). Next to vehicle design measures, also infrastructure changes can be made to improve road safety regulation compliance (see, Alvarez et al., 2007; Ewing and Dumbaugh, 2009). The conventional theory of road design is that wider, straighter, flatter, and more open is better from the standpoint of traffic safety. However, the land-use context and vehicle-operating conditions are entirely different in urban than rural areas. Thus, based on empirical evidence (for an overview, see Ewing and Dumbaugh, 2009), it turns out that road infrastructure measures should be different for urban roads or for rural roads and highways. For instance, in an urban context, the safest streets were narrow, slow, 7.3 meter wide streets in Longmont, Colorado (US) (Swift et al., 2008).

When looking at the effectiveness of these engineering solutions, well-designed measures that take into account local characteristics can indeed increase traffic safety (for an overview see, Ewing and Dumbaugh, 2009). However, two important topics need to be addressed. Firstly, we discuss the presence of rebound effects. Since technological studies analyzing the effect of safety devices in cars often neglect the offsetting effect of the behavioral response by drivers, they are likely to overstate the improvements in traffic safety that can be expected from them (see Peltzman, 1975). For instance, wearing seat belts improves drivers' safety. However, since the expected negative effects from risky driving are reduced, some drivers might start driving less careful. These offsetting, or rebound, effects would then lead to a higher number of non-fatal accidents and a higher number of deaths among pedestrians than initially expected. Secondly, it should be noted that the use of technological solutions in road safety enhancement does not deter all recidivism in practice. For instance, ignition interlock license restriction programs can significantly reduce recidivism among drivers with multiple alcohol traffic violations, but recidivism does not necessarily reduce to zero. This was demonstrated for the interlock program in Maryland (US) by Beck et al. (1999). The study found that being in this interlock program reduced a driver's risk of committing a violation within the first year by approximately 64%, while the effect in the second year was not statistically significant.[1]

[1] Beck et al. (1999) used random assignment of offenders into the experimental (interlock) or the control program.

B. INFORMATIONAL AND EDUCATIONAL PROGRAMS

Public information and education campaigns are also used to try to increase drivers' compliance with road safety regulation. These campaigns range from mandatory driver education to awareness increasing measures such as press releases, outreach programs to local schools or interest groups, the distribution of leaflets, and the use of websites.

However, when it comes to effectiveness, the results of these informational and educational programs are often inconclusive and show only limited effects (see, among other studies, Tay, 2005a; Son et al., 2009; Brijs et al., 2009). In an Australian study, Donovan et al. (1999) have, for instance, investigated twelve road safety television commercials covering speeding, drink driving, fatigue and inattention. Their results are based on respondents' answers with respect to the likelihood of complying with the recommended behavior as a driver and, as a passenger, the likelihood of influencing the driver to comply with the recommended behavior. The stated effects of the advertisements range from around 19% to 60%, both as a driver and as a passenger. In a series of more recent studies, Tay (2005a; 2005b) focuses on the actual effect of publicity campaigns on crash risks in Australia. Anti-drunk driving advertisements have a significant impact in reducing the number of serious crashes during high alcohol hours in Victoria (Australia). The effects occur mostly in the first three years of campaign implementation (Tay, 2005a). Surprisingly, in Australia the advertising campaign was almost as effective as the enforcement campaign using random breath tests (at the current level of input and expenditure). Further, it is interesting to investigate whether publicity campaigns act as a complement or a substitute for conventional enforcement. Tay (2005b) showed that enforcement and publicity campaigns focusing on drinking and driving had a significant independent effect in reducing crashes for young male drivers in Victoria (Australia) and both measures did not reinforce or complement each other. On the other hand, enforcement and publicity campaigns focusing on speeding had no independent effect, but their interactive effect was significant in reducing serious crashes involving young male drivers.

C. REGULATION

Governments can also use different regulatory instruments (REG) to improve road safety and decrease accident risks. These instruments include drivers' age limits, limits on drivers' blood alcohol levels, speed limits (e.g. Graves et al., 1989), obligatory seat belt use, beer taxes, drinking age laws (e.g. Saffer and Grossman, 1987) and the imposition of liability regimes such as dram shop laws (i.e. establishments serving alcohol can be held at least partly liable for ensuing crashes involving alcohol) or tort liability (e.g. Sloan et al., 1994). While it is clear that the effect of these regulations on road safety depends on the type of policy instrument used within a particular setting, the compliance incentives associated with these regulations also depend on the type and the stringency of the selected policy.

Looking at the effectiveness of regulatory approaches, we focus on regulation related to drinking and driving. Several regulatory measures can indeed positively influence road safety. We discuss some empirical findings for minimum drinking age regulation, legal blood alcohol limits and beer taxes. Firstly, a higher minimum drinking age is found to reduce the number of traffic accidents (e.g. Saffer and Grossman, 1987; Asch and Levy, 1987). However, if the minimum drinking age acts as an indicator for experience with drinking, this might also explain the observed decrease in accident risk. The relationship between drinking experience and accident risk was observed by Asch and Levy (1987) in state-level cross section data analysis for the US. Thus, it is possible that effectiveness of drinking age as a traffic safety policy tool is relatively limited. Secondly, a decrease in the legal blood alcohol level also tends to have a positive effect on road safety, at least when the associated enforcement level is sufficiently high (see, e.g., Homel, 1994; Eisenberg, 2003). Thirdly, higher beer taxes have a significant and robust negative effect on crash-related deaths (see, e.g., Saffer and Grossman, 1987; Ruhm, 1996; Levitt and Porter, 2001). Still, while higher beer taxes lead to a lower number of drunk drivers, they might also lead to a higher traffic safety risk per drunk driver (see, e.g. Levitt and Porter). This phenomenon is consistent with the hypothesis that higher beer taxes mainly deter small-scale offenders, who adjust their behavior and drive more carefully, but that these taxes do not greatly affect the serious drunk-driving offenders. In general, it seems that the impact on traffic safety from an increase in beer taxes is higher than that from a decrease in BAC limits.

D. ENFORCEMENT THROUGH MONITORING AND SANCTIONING

According to standard rational choice theory, road users comply with traffic regulations if the expected utility of law-abiding actions is greater than the expected utility associated with violating the law (Becker, 1968). With some simple re-interpretation, this same insight also follows from the conceptual model presented in section 2 as well as the model used by Bjornskau and Elvik (1992). Enforcement actions can lead to both specific deterrence and general deterrence (Homel, 1988; Shavell, 1991). General deterrence follows from the overall level of monitoring and sanctioning activities, while specific deterrence follows from an individual's personal experience with monitoring and sanctioning actions.

Further, standard economic compliance models typically assume that monitoring is costly, but that sanctioning is costless to society (see, for instance, Becker, 1968, Polinsky and Shavell, 1979; Shavell, 2004). For this reason, those compliance studies typically show that fines should be set at the highest possible level and that minimal (costly) monitoring efforts should be implemented. However, in practice we see large variations in the magnitude of speeding fines and in the probability of detection between European countries (European Commission, 2004). Bjornskau and Elvik (1992) have noted that it is difficult for the police force to credibly

commit to continued, stringent road traffic enforcement, when compliance levels are increasing. One possible solution to this problem is the use of automated monitoring devices such as speed cameras. Next we discuss the two complementary elements of enforcement, monitoring (p_s) and sanctioning (S), in more detail as well as the interaction between both. The effectiveness of enforcement in practice is discussed separately in section 5.

1. Monitoring

Monitoring of traffic violations is crucial in creating a positive probability that a violator is sanctioned. This probability of sanctioning is composed of the product of the probability that a violation is detected, the probability that the offender responsible for a detected violation is identified, the probability that an identified offender is prosecuted and the probability that a prosecuted offender is sanctioned by the enforcing authority (administrator, police court judge, criminal judge…). There are two main methods of road traffic monitoring (SafetyNet, 2009): the first is to check drivers alongside the road and the second method is based on automated monitoring devices. The first technique is also called stationary monitoring or physical policing and can include, among other things, mobile speed cameras, random road-side breathing tests, and checks on seat belt use or truck driver fatigue. Automated monitoring, on the other hand, is mainly used for speed monitoring and red light running.

Looking at frequency of monitoring, there is a general consensus that monitoring strategies focusing on particular groups of high likelihood offenders outperform more uniform strategies when it comes to deterring potential offenders (see, e.g., Harrington, 1988). Monitoring actions should therefore concentrate on periods or locations where violations of traffic regulations are more likely or have more serious consequences. Thus, it makes sense to focus on weekend nights since the frequency of drunk drivers is more likely to be higher than during weekdays. Also, it might pay off to increase monitoring near road works, since speed offenses are more likely on those road sections and the consequences a traffic accident can be especially severe. Further, it might also be beneficial to focus on intermittent periods of high intensity monitoring rather than continuous low intensity monitoring, as shown be Eeckhout et al. (2010).

To get an indication of the stringency of speed monitoring, we mention some results of the SARTRE 4 survey (SARTRE, 2012). SARTRE 4 contains survey results from 19 European countries: Austria, Belgium, Cyprus, Czech Republic, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, The Netherlands, Poland, Serbia, Slovenia, Spain and Sweden. The subjective probability of detecting a speeding offense is perceived by respondents to be quite low in Europe. On average 29% of the respondents did not believe that driving 20 km/h over the speed limit in a residential area would lead to them being stopped and fined by the police, while 54% stated that they would 'never' or 'rarely' be checked for speeding on a typical journey. Nevertheless, some 24% of the respondents acknowledged that they were

fined or received another penalty for speeding during the last three years. Some 27% (strongly) disagreed with the statement that penalties for speeding should be more severe.

In relation to drunk driving, Beck et al. (1999) state that 'several studies have estimated that a driver would have to drive drunk at least 200 times before being arrested once'. According to SARTRE 4 (2012) about three in five car drivers (58%) have not been checked for alcohol in the past three years in Europe. Further 23% of car drivers was checked only once and the remaining 18% more than once in the past three years.

2. Sanctioning

Next, we discuss different characteristics of sanctioning of detected road traffic violations. Regulators can choose between several types of sanctions such as administrative and criminal fines, point systems, license suspension, license withdrawal, mandatory alcohol locks, and even imprisonment. In general, sanctions consist of two parts: one part that is independent of the seriousness of the offense and one part that is dependent on the degree of violation. For instance, speeding fines typically include a fixed amount and a variable amount depending on difference between the measured speed and the speed limit.

Another general characteristic of sanctioning in practice is that repeat offenders are often sanctioned more harshly than first-time offenders. Point systems are here a typical example. A differentiated fine structure that depends on past compliance can be optimal for traffic violations (Delhaye, 2007), since targeted monitoring of drivers is very difficult to realize in practice. Related to this issue of differentiated sanctions is the role of warnings in traffic enforcement, since warnings can be interpreted as a way to be lenient to first-time offenders. The dominant rationale behind the use of warnings is that an uninformed individual is allowed to learn what illegal driving behavior is and that sanctions should only be imposed on informed individuals. However, if measurement errors occur (e.g., Rousseau, 2009) or if drivers are not learning anything after a warning is issued, then warning systems lead to under-deterrence (e.g., Basili et al. 2012). Such a warning system is in reality often executed as a type of points system in which drivers can gain (or lose) points when particular violations are committed and detected. When the maximum allowed number of points is reached (or all points are lost), the driver's license is suspended (Castillo-Manzano and Castro-Nuño, 2012). In recent years, the number of these points systems is rapidly expanding in high income countries, especially in the European Union.

Further, sanctions are not always determined in an optimal way since interest groups might try to influence policy or because regulators might be driven by private considerations. For example, Makowsky and Stratmann (2009) empirically estimated the influence of incentives faced by police officers and their principals (who aim to maximize votes) on the issuing of speeding tickets in Massachusetts (US). Their findings confirm that the size of the violation was not the sole determinant of the fine. Fines were also determined by the police officers' objective functions and the incentives that they faced.

3. Interaction between monitoring and sanctioning

As was shown in section 2, driver compliance is determined by the product of the sanctioning probability (p_s) and the imposed sanction (S). Thus both decision variables need to be considered simultaneously. This trade-off between the probability and the level of the sanction depends crucially on the risk attitude of drivers (Polinsky and Shavell, 1979; 1992; 2000).

Firstly, assuming drivers are risk neutral, private decisions by drivers will be optimal if the expected penalties equal the value of the risks a driver imposes on others (see also Kenkel, 1993). The faster one drives, the higher the expected damage and hence, for a given probability of detection, the higher the fine should be. As mentioned by Delhaye (2007), this closely coincides with reality, since in all European countries the fine increases with the level of speeding.

Secondly, in the presence of risk-averse individuals, the optimal fine level is shown to be lower than the maximal fine when measurement errors occur (Polinsky and Shavell, 1979). If car drivers are risk averse, they prefer a high probability of detection combined with a lower fine to a lower probability and a higher fine with the same expected value (Rothschild and Stiglitz, 1970; 1971). Bar-Ilan (2000) studied the risk attitude of road users in his analysis of the behavior of red light runners. Red light runners were shown to be risk lovers. This might explain why they are not deterred by high expected damages (injuries or even death) when the probability that these damages occur are low.

V. EMPIRICAL EVIDENCE OF THE EFFECTIVENESS OF ROAD SAFETY ENFORCEMENT

While we discuss monitoring and sanctioning in general terms in the previous section 4.4, we now study the effectiveness of road safety enforcement measures in practice. Again, we discuss three types of violations – seat belt use, drunk driving and speeding – and end with some general results that exceed the level of one particular violation. We focus on empirical studies showing the impact of different types of monitoring actions or different types of sanctions.

A. SEAT BELT USE

Since many drivers do not voluntarily buckle up, enforcement of seat belt use regulation plays an important role. As a rule, the empirical evidence confirms that enforcement positively stimulates seat belt use. The size of the effect, however, depends on the type of regulation in place (see e.g. Campbell, 1988 and Shults et al. 2004 for a US example) and the amount of publicity associated with the enforcement actions (see, e.g., Williams and Wells, 2004).

Turning to some specific results, Campbell (1988) statistically demonstrated a causal relationship between enforcement and seat belt use for the US. This analysis suggests two additive factors at work. First, in both primary enforcement states (i.e. a police officer can stop a driver solely based on a seat belt violation) and secondary enforcement states (i.e. a belt law violation may be addressed only if the officer has stopped the driver for some other violation), belt use is higher in the presence of higher levels of enforcement. Second, for a given level of enforcement, belt use is higher in primary than in secondary enforcement states. These results were later confirmed by Shults et al. (2004).

Based on a review of different enforcement programs, highly publicized enforcement programs proof to be a reliable technique for increasing seat belt use in Canada, the United States, and other countries (Williams and Wells, 2004). Police agencies play a central leadership role. The road safety programs that were more effective seem to have some common characteristics: increased publicity about the importance of using seat belts, greatly increased law enforcement, and publicity aimed at increasing visibility and awareness of the enforcement actions (Williams and Wells, 2004).

B. DRUNK DRIVING

Looking at drunk driving enforcement, empirical evidence again confirms that more stringent enforcement leads to higher compliance levels, irrespective of country-specific factors (see, e.g., Tay, 2005c; Levitt and Porter, 2001; Eisenberg, 2003; Mathijssen, 2005). In line with the results presented for seat belt use (section 5.1), the type of regulation in place (see Eisenberg, 2003) and the joint use of publicity campaigns (see Mathijssen, 2005) seem to influence the size of the reduction in violations.

We now turn to some specific results. Firstly, the difference between general and specific enforcement has been studied. For instance, Homel (1988) analyzed how general and specific deterrence function in the context of deterring drunk persons from driving. Using prospect theory he argued that even though detection probabilities are generally low, they may be overrated in the perception of potential drunk drivers. Secondly, he showed that individuals' perceptions of being detected are affected when one of their acquaintances is detected or even simply monitored. These mechanisms drive the general and specific deterrence effects of police monitoring on compliance. Tay (2005c) estimated the general and specific deterrent effects of traffic enforcement in Queensland (Australia). He found that both the number of breath tests performed per month (general enforcement) and the percentage of drivers apprehended (specific enforcement) had a significant effect in reducing the number of serious crashes per month.

Moreover, empirical studies find evidence for the hypothesis that penalties for first-time offenders mainly deter small-scale offenders, whereas increased police force and penalties for repeat offenders mainly deter serious offenders (or chronic drinkers). For instance, Levitt and Porter (2001) found that tougher penalties for first-time offenders led to a lower number of drunk drivers, but to a higher traffic safety risk (per drunk driver) in US. In contrast, tougher

penalties for third-time offenders and a higher number of police per capita had a negative effect on the risk per drunk driver. Later, Eisenberg (2003) also evaluated the effectiveness of US state-level public policies related to drunk driving using a panel dataset. His results revealed that graduated licensing programs for young drivers are effective in reducing fatal crash rates for all drivers by 4 percent. Other policies that were significant in the US in reducing fatal crash rates were open container laws (i.e. restrictions or bans on open containers of alcohol in vehicles), dram shop laws, seat-belt laws and beer taxes. For The Netherlands Mathijssen (2005) observed that drink driving policies have been fairly successful in reducing drink driving. The key factor was the increase in the level of police enforcement, combined with the introduction of random breath testing and increased publicity. However, a part of the population remained difficult to deter. This is especially the case for high BAC drivers, combined alcohol and drug users, and young males.

C. SPEEDING

Regarding speeding offenses, different types of enforcement actions have been studied in various settings. The same general trend is observed: more stringent enforcement leads to higher compliance. However, the relative effectiveness of different monitoring options (e.g. mobile vs. fixed speed cameras, police presence or average speed control) varies according to the circumstances. Also, some limitations of monitoring actions have been identified. While speed camera enforcement is found to be effective in reducing speeds, the effects can be temporary and local. This phenomenon is called a limited distance halo and a limited time halo (SWOV, 2011). According to some studies (e.g. Elvik, 2009; SWOV, 2011), speed monitoring using speed cameras or physical policing might even have some potentially perverse effects. These negative effects include the so-called kangaroo effect and the crash risk migration effect. A kangaroo effect is created when drivers brake suddenly upon noticing a speed camera or a police car and then quickly accelerate again. Such a kangaroo effect can lead to a crash migration effect when crash risk shifts from one location to another. Another cause of crash risk migration can be the redirection of traffic flows and the change in perceived crash risks when the infrastructure or the speed limit at a particular black spot (i.e. place with high accident risks) is adapted. However, no conclusive empirical evidence of these effects exists, possibly due to the scarcity in empirical studies examining this effect (SWOV, 2011). We now look at the results for some specific enforcement instruments into more detail: namely speed cameras, police presence, average speed control and increased fines.

Firstly, enforcement of speed limits by speed cameras was generally effective and speed cameras indeed reduce speeding when used properly (Willis, 2006; SafetyNet, 2009; Allsop, 2010; Debnath et al., 2012). For the US, Joerger (2010) found that speed cameras resulted in a 27% reduction in speed in a 40 miles per hour zone in Oregon, while Huebschman et al. (2003) reported a 19% reduction in average speeds during active speed camera enforcement. For the UK, Gains et al. (2004) described that the number of vehicles that exceed the speed limit

dropped 71% at fixed camera sites and 24% at mobile camera sites. Looking at other countries, evidence of the effectiveness of speed cameras in reducing speed is also found in Australia (Belin et al., 2010), New Zealand (Keall et al., 2001, 2002), The Netherlands (SWOV, 2011), Sweden (Belin et al., 2010), and Norway (Elvik, 2009). The positive effects of speed cameras have been obtained both with visible cameras and with hidden cameras (e.g. Keall et al., 2001, 2002). However, the positive effects of cameras turn out to be limited both in time and in place. For example, Joerger (2010) found that speeding returned to pre-enforcement levels immediately after removal of the camera in Oregon (US). Also the SWOV review (2011) mentions that the effects disappear within a few days after camera surveillance is stopped. With respect to spatial effects, the impact of speed cameras is generally limited from just a few kilometers to approximately ten kilometers past the camera location. When the cameras are easily visible or when visible fixed cameras and hidden mobile cameras are used in combination, this distance halo is found to be larger (SWOV, 2011).

Secondly, visible police presence is also found to be an effective speed control measure (Arnold Jr, 2003; Benekohal et al., 1992; FHWA, 1998; Huebschman et al., 2003). Road users infer that there is a high likelihood of enforcement, whether or not enforcement is actually carried out. For instance, Hajbabaie et al. (2009) examined the effects of four different measures for speed control at roadwork zones in the US, including photo-radar van, speed feedback, police car without lights flashing, and speed feedback with police car without lights flashing. Each measure was effective in isolation, but the largest reductions in average speed and in the degree of speeding were achieved with police presence in conjunction with speed feedback. Unfortunately, physical police presence is very labor intensive, and therefore quite expensive. Overall opinions on the effectiveness of physical police presence are mixed: Debnath et al. (2012) claim that physical policing is more effective than speed cameras, while SafetyNet (2009) concludes that speed cameras are more effective than physical policing in reducing speeds and crashes.

Thirdly, average speed control, also called section control, is a monitoring technique which measures the average speed of drivers over a road section of several kilometers (SafetyNet, 2009). As a rule these systems work on a permanent basis, which makes the probability of detection close to 100% (although not the probability of sanctioning). As a case in point, RWS (2003) found that average speed control reduced the number of speed offenders to less than 1% at an enforced section of highway in the Netherlands.

Fourthly, the effect of increasing penalties has been studied. One approach, followed by Debnath et al. (2012), compared speeding in road work zones to speeding in other locations since fines are doubled at work zones in the US regulation. However, evidence for the effectiveness of higher fines seems to be rather weak (Ross and Pietz, 2011; Ullman et al., 2000). A study at worksites in Texas (US) prior to and after implementation of higher penalties found that half of the sites showed no significant changes in speed, 28% of the sites observed decreased speeds, and 22% of the sites surprisingly observed increased speeds (Ullman et al., 2000). The ineffectiveness of the higher penalties could be due to an

apparent reluctance of courts to apply penalties in full (Arnold Jr, 2003). Proper enforcement was also problematic because of the physical nature of the road work. Often road works involve narrow carriageways or using the shoulder lanes for traffic movement or carrying out the works. This makes it difficult for police officers to stop a speeding driver. These monitoring problems might potentially be overcome by using automated monitoring techniques.

D. SOME GENERALLY RELEVANT RESULTS

We now look at some results which are relevant for different types of offenses and focus on the link between road traffic enforcement and accident reduction. This information is needed for the regulator to select an optimal level for each of the available options mentioned in the conceptual model. In general, we can say that road traffic enforcement reduces accident risks. However, some topics require some additional discussion. We look at the relevance of previous traffic convictions, the effect of police presence and the role of warnings and imprisonment as a deterrent.

Firstly, we look at the relationship between previous traffic convictions and crash risk. On the one hand, drivers with past convictions might have learned from the past and become more careful in the future. Under this assumption, crash risk would decrease for drivers with prior convictions. On the other hand, past convictions can be used as a proxy to increase enforcement for drivers with a higher accident risk (i.e. for targeting). This interpretation provides a rationale for increasing sanctions for repeat offenders, which is a strategy frequently observed in practice. The first interpretation was tested in Canada by Redelmeier et al. (2003). They studied whether traffic convictions have an impact on risk of fatal motor-vehicle crashes. They use individual data of licensed drivers in the province of Ontario, who have been involved in fatal crashes over an eleven year period. The risk of a fatal crash in the month after a conviction was found to decrease with about 35%. The benefit was lower in the two month period after the conviction and became insignificant after three to four months. This provides evidence of a decreasing time halo effect. However, Redelmeier et al. (2003) did not find any evidence for reduced risk of fatal accidents following a conviction in cases where driving licenses were suspended.

Secondly, the effect of police presence on driver behavior is worth some attention. Studies of Arnold Jr (2003), Benekohal et al. (1992) and FHWA (1998) found that visible police presence was an effective measure to control excessive speeding. Walter et al. (2011) conducted a study in the UK to analyze the impact of police presence on different types of traffic violations. Two teams of six officers and one sergeant were deployed in two shifts per weekday on a six mile route, using both static and mobile policing methods in different vehicles. The results showed that vehicle speeds reduced systematically during the operation along the route and in surrounding areas, and some effects remained at least

two weeks after the operation had finished (proving the presence of a time halo effect). The data did not, however, show any positive effect of enforcement measured by a possible reduced use of mobile phones or improved seat belt use. These results are in line with previous studies when it comes to speeding offenses, but they are different for other types of offenses.

Thirdly, to test whether warnings induce learning by uninformed drivers, Basili et al. (2012) used longitudinal data on drivers under the demerit point system of traffic enforcement introduced in Italy in 2003. Each Italian driver is given a number of points (20) and detected traffic violations lead to a reduction in those points (1 to 10 depending on the severity of the violation). Driver suspension only happens when the stock of points is exhausted. Basili et al. (2012) found that, on average, the higher the number of residual points a driver holds, the more likely (s)he is to commit an additional traffic violation. The authors interpret this result as implying that warnings do induce an uninformed driver to learn about legal and illegal driving behavior. This observation is in line with the results found by Chandler (2012) in Canada. He observed that the threat of losing a driver's license only affects drivers close to the limit. This threat reduces the probability of violation by 50 to 80 percent. A recent meta-analysis of point systems can be found in Castillo-Manzano and Castro-Nuño (2012). Their analysis allows the authors to estimate that, after implementation of a point system, road traffic accident-related hospital admissions reduced by over 50%, the number of law violations and risky driver behaviors reduced by around 30% and, most importantly, the number of accidents, fatalities and injuries reduced by 15 to 20%. Unfortunately, these positive effects were not found to carry over to the long term, since the effects seem to wear off in less than 18 months. To stimulate long term behavioral changes, the implementation of a point system should be complemented with adequate enforcement activities and major advertising campaigns.

Fourthly, the impact of including imprisonment as one of the sanctions applicable to road traffic offenses on accident rates is discussed. Using imprisonment as a sanction is only possible if traffic offenses are classified as criminal offenses. Castillo-Manzano et al. (2011) have examined the impact of the Spanish Penal Code reform, which allowed for the criminalization of traffic offenses, on the number of road deaths in Spain. A month before the reform was passed, there was a 24.7 percent fall in Spanish road deaths. After the Bill had been passed in December 2007, the reduction stayed at a constant sixteen percent for the following thirteen months.

To end, it should be noted that traffic enforcement may have positive externalities on other types of criminal offences, because criminal activities are sometimes detected through the use of random roadblocks. The House of Commons Transport Committee (2004) argued in this sense: effective traffic law enforcement can help to prevent other types of criminal activities because serious and chronic traffic law offenders are often also involved in committing other types of crimes.

VI. CONCLUSIONS

In order to structure the literature related to road safety enforcement, we developed a simple conceptual model to understand how road users decide on optimal precautionary measures. This model also laid out a framework for understanding the different policy instruments available to regulators, their interactions and the conditions that determine the optimal level of policy intervention. Next we examined how the different model variables and functional specifications can be interpreted in practice. Also, we looked at the empirical evidence that can be found to substantiate the effectiveness of the different policy options.

To start, we investigate the relationship between road user behavior and road safety. We impose further structure on the discussion by making a subdivision in speeding behavior, drunk driving and seat belt use. We highlight the relationship between preventive actions taken (PREV), individual accident risk (AR_{priv}) of interest to the road user and total accident risk (AR_{tot}) of interest to the regulator. Next, we take a closer look at instruments available to the regulator to improve road safety behavior by road users. This discussion is structured along the different regulatory instruments that are outlined in the regulator's objective function of our conceptual model. We investigate engineering and technological approaches (TECH & VEH), we look into informational campaigns (INFO), we dwell on regulation actions (REG) and we investigate enforcement actions (p_s & S). Finally, we focus on effectiveness of different road safety enforcement measures in practice. We look at specific studies conducted in the context of speeding, drunk driving and seat belt use. We can also draw some conclusions which are not domain-specific, but have broader relevance.

It is clear that enforcement as a stand-alone measure is insufficient to substantially increase road traffic safety. The different policy instruments tend to interact and can generally be thought off as being complements. An effective road safety policy should thus combine several actions including engineering measures, regulatory actions, informational campaigns and road enforcement. Such a multi-faceted approach is required to address the multiple, and often diverse, causes of road traffic accidents. Attributing factors of road accidents include inadequate infrastructure, technical failures, driver inattention as well as a range of risky, and often illegal, behaviors by drivers. One policy instrument cannot possibly address these different aspects. As Phillips et al. (2011) mention in a recent overview of the effectiveness of road safety campaigns: 'enforcement is important in consolidating the effects of large scale campaigns'.

We have focused this review on the effectiveness of enforcement actions for three prominent traffic violations, namely speeding, seat belt use, and drinking and driving. For these violations, we observe that several enforcement measures are available and able to decrease the number of violations. Both visible and hidden speed cameras stimulate drivers to reduce their speed, although this positive effect is shown to be limited in distance and in time. Regarding seat belt use, a mix of legally imposing seat belt requirements, enforcement

and publicity campaign seems to be most effective in reality. Finally, enforcement of drunk driving policies has been fairly successful in several countries based on a combination of random breath testing and increased publicity. In general, it is shown that a single enforcement measure is insufficient to substantially reduce accident risk in the long term. Compliance enhancement strategies combining several measures are generally more effective, irrespective of country-related or policy-related differences.

Overall, the success of road traffic enforcement depends on its ability to create a meaningful deterrent threat to road users. To achieve this, two approaches can be used. Firstly, by ensuring a sufficient level of monitoring and a sufficiently high probability of detection deterrence can be increased. Secondly, by ensuring credible and sufficiently stringent sanctions, deterrence will be higher. While in theory these approaches are often treated as substitutes, in reality they are more likely to be complements.

Finally, as a rule the goal of road traffic enforcement is to minimize the number of accidents and thus effectiveness of enforcement measures is assessed by their ability to reduce accidents. Implicitly this assumes that the ultimate goal is to reduce the number of road traffic accidents to zero, irrespective of the costs. Thus, we find many empirical studies examining the effect of road enforcement measures in reducing traffic violations and/or in reducing accident rates. However, the costs of these enforcement measures are only rarely taken into account. Policy evaluations of road enforcement using cost effectiveness analysis or cost benefit analysis are therefore scarce (see, e.g., Tay 2005a). They are much more common when it comes to the evaluation of (major) infrastructure projects or general road safety programs. Elvik et al. (2009) have estimated the benefits associated with funding in transportation research in Sweden. They found that the benefits of applied road safety research are likely to be greater than the costs of conducting this research, and implementing the road research-based safety measures. Therefore, additional studies are certainly worthwhile in which the costs of different enforcement measures are taken into account. Their goal is to ensure maximal compliance with traffic regulations under a budget constraint. In order to optimize traffic safety regulations all relevant costs and benefits should be taken into account. Focusing on the benefits (or the effectiveness) only is clearly a one-sided and inefficient approach.

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