The role of average speed enforcement systems in preventing highway accidents: evidence from Italy

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Abstract

At the end of 2005, Autostrade per l'Italia and the Italian traffic police progressively deployed along the Italian tolled motorway network an average speed enforcement system, named Safety Tutor, able to determine the average speed of vehicles over a long section to encourage drivers to comply with speed limits and improve safety. Although promoters of Safety Tutor credited it with a sharp decrease in highway accidents all along high-speed roads, previous studies have estimated the impact of this intervention only in specific motorway sectors with unique road and congestion features. The novel contribution of this paper lies in the evaluation of the effectiveness of Safety Tutor in reducing highway accidents at the national level during the period 2001-2015 by using a unique panel dataset that makes it possible to control for many unobserved factors and that exploits the heterogeneity within all motorway sectors. We find that a 10% increase in Safety Tutor coverage is associated with an average reduction in total accidents (-1.3%), injuries (-1.0%), fatalities (-3.6%), and light vehicle accidents (-1.4%). However, to address persistent endogeneity issues in accident analysis contexts, we utilize an instrumental variable (IV) strategy by exploiting the membership of some motorway sectors in the Autostrade per l'Italia group as an instrument for Safety Tutor. The IV estimates reveal no evidence of a significant causal effect of the average speed enforcement system on preventing highway accidents in any of the categories analysed. This study can help highway concessionaires and road agencies in analysing their increasing amount of available data through robust econometric methods to better evaluate accident prevention policies and the relative allocation of resources.

Keywords: Highway safety, Accidents, Average speed enforcement system, Safety Tutor, Policy evaluation

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1. Introduction

Speeding has been recognized as one of the major causes of road accidents (Aarts and Van Schagen, 2006; Hauer, 2009; Montella et al., 2011, 2015b; Yannis et al., 2013), and the relationship between speed and crash risk has been extensively investigated (Neuman, 2003; Montella and Imbriani, 2015). Thus, in an attempt to reduce speeding across road networks, most road agencies have adopted a variety of policies to improve safety such as camera-based speed enforcement approaches.

Several studies have confirmed the positive effect of fixed and mobile speed cameras on vehicle accident reduction on both rural roads and motorways (Goldenbeld and van Schagen, 2005; Jones et al., 2008). However, the cameras' contribution has been shown to be limited to the immediate vicinity of the enforcement activity, achieving speed reduction on only a short section (Champness et al., 2005; De Pauw et al., 2014b). In addition, speed variation between vehicles (due to speed-check cameras) has also been demonstrated to increase the risk of becoming involved in an accident because sudden braking may disrupt homogenized traffic flow and reduce headway distances between vehicles (Cirillo, 1968; Transportation Research Board, 1998). Consequently, since there is evidence that many drivers regard speeding as normal and socially acceptable (Fleiter et al., 2010; Veisten et al., 2013), the need emerged for an innovative speed management system that balances safety with the efficiency of vehicle flows on the road network (Wegman and Goldenbeld, 2006).

This relatively new technology, called an automated average speed enforcement system, is able to determine the average speed of vehicles over a long section by dividing the certified and known distance between two camera sites by the time the vehicle takes to travel between those two sites, thereby encouraging speed compliance over a greater distance (Soole et al., 2012) and eliminating the need for police officers at the scene. Moreover, it provides a nearly perfect probability of catching drivers when speeding (Aarts et al., 2009; Montella et al., 2011). Initially operated in trial form in 1997 in the Netherlands, this system has achieved promising results, resulting in its increased popularity in several highly motorized countries.

In Italy, to improve safety on high-speed roads, a point-to-point (P2P) speed enforcement system, named Safety Tutor, was developed by Autostrade per l'Italia (the major highway concession company) and the Italian traffic police in 2004 and progressively deployed along the Italian tolled motorway network starting on 23 December 2005. By 2018, more than 3 100 km of the highway network (considering both carriageways) were monitored by the system through 333 P2P sites. However, after a 12-year legal process, on 10 April 2018, the Court of Appeals of Rome established that patent rights related to the Safety Tutor technology belonged to another company (Craft S.r.l.), therefore forcing Autostrade per l'Italia to remove the device. In the following months, all Safety Tutor sites were turned off in anticipation of their replacement.

Over time, Autostrade per l'Italia, newspapers, and specialized magazines have underlined how this intervention significantly changed drivers' behaviour all along high-speed roads, achieving promising results in preventing highway accidents (Falsi, 2009; Autostrade per l'Italia, 2016). However, previous studies have analysed the effect of Safety Tutor only on specific motorway sectors with unique road characteristics and congestion features. Therefore, the aim of this paper is to detect the extent to which Safety Tutor has significantly contributed to improving driver safety at the national level to provide a tool that highway concessionaires and transport policy makers can use to evaluate any benefits associated with average speed enforcement systems, determine the allocation of resources, and assess whether it is worth replacing this device or extending its coverage.

For this purpose, the novelty of the present paper lies in performing the first evaluation of this device on a substantial scale by using a unique 15-year panel dataset to analyse the influence of Safety Tutor on five different types of accident categories in the Italian tolled motorway network during the period 2001-2015: total accidents, injuries, fatalities, light vehicle accidents, and heavy vehicle accidents. The second source of novelty lies in exploiting the heterogeneity within all motorway sectors by including both those that have installed the device and those that have not. In particular, the analysis takes into account those motorway sectors under concession to 24 private, public, or mixed capital companies that represent nearly 85% of the national highway network (the remaining toll-free 15% is managed by ANAS, a government-owned company under the control of the Ministry of Infrastructure and Transport).

By exploiting the longitudinal structure of our dataset, which allows us to control for many unobservable confounding factors, OLS estimates identified a much lower impact of Safety Tutor coverage on reducing highway accidents in comparison to previous studies. In particular, a 10% increase in Safety Tutor coverage is associated with an average reduction in total accidents by nearly 1.3%, injuries by 1.0%, fatalities by 3.6%, and light vehicle accidents by 1.4%. However, after controlling for additional endogeneity issues through an instrumental variable strategy, the results suggest that there is no evidence of a significant causal effect of Safety Tutor on preventing accidents in any of the categories analysed.

The paper is structured as follows: Section 2 briefly describes the Safety Tutor technology and reviews previous studies, Section 3 describes our data collection procedure, Section 4 describes the patterns of Italian highway accidents over time, Section 5 specifies our econometric model, and Sections 6 and 7 provide OLS and 2SLS estimation results. Section 8 provides robustness checks, while Section 9 summarizes the paper's findings and critically analyses some of its drawbacks.

2. The Safety Tutor system and previous evaluations

Safety Tutor, exclusively managed by the national traffic police, is composed of a series of steel gantries installed at multiple locations along a high-speed road section, each one covering from 10 to 15 km. High resolution cameras with infrared flash are mounted on the gantry, one for each lane. Whenever a vehicle crosses over the initial camera site, the lane-related camera records its date and time. Then, these data are processed by an automatic video-based vehicle identification software for vehicle plate recognition that matches vehicle class and registration details. When the same vehicle crosses the exit section, the same operation is performed. As a result, if the calculated average travel speed between the entrance and the exit sections exceeds the speed limit (plus a tolerance equal to a maximum between 5 km/h and 5% of the speed limit), the system automatically follows up with an offence citation to the vehicle owner, ensuring strict and equitable enforcement (Montella et al., 2012, 2015b).

A comprehensive international review of all available studies evaluating the effectiveness of average speed enforcement systems (Soole et al., 2013; International Transport Forum, 2018) elucidates their positive contribution to a variety of road safety and traffic-related outcomes such as accident rates, speeding offence rates, traffic flow, and vehicle emissions (Stefan and Winkelbauer, 2006; Collins and McConnell, 2008; De Pauw et al., 2014a). To date, after more than 10 years of operation, previous studies analysing these effects within the Italian context are still limited to specific motorway sectors. A naïve before-after analysis with pre- and post-implementation periods showed significant reduction in both average speeds (-15%) and peak speed (-25%), with consequent improvements in the injury rate (-27%) and in the mortality rate (-50%) on Safety Tutor sections after 12 months of operation (Galata, 2007; Falsi, 2009). More recently, Autostrade per l'Italia underlined a further reduction in the mortality rate by 80% on its network (Autostrade per l'Italia, 2016). However, it is important to note that statistical significance testing and the control of confounding factors were absent from these evaluations.

A more reliable evaluation was provided by Cascetta and Punzo (2011) that showed that Safety Tutor installation on A56 Tangenziale di Napoli produced a mean speed reduction from 80.8 km/h to 71.7 km/h by comparing vehicle data from 1-week pre to 1-week post activation on February 9, 2009. Furthermore, comparing total accidents between 8 months pre- and 8 months post-installation demonstrates a significant reduction from 116 to 71 (-38.8%). Consistent with the previous study, Montella et al. (2015b) estimated through an empirical Bayes methodology an average speed reduction for light vehicles from 83.4 km/h to 75.2 km/h within the same A56 Safety Tutor sites by monitoring vehicle speed over four periods between 2009 and 2011. The longer time span under analysis allowed them to observe a significant increase in non-compliance behaviour towards speed limits over time with respect to results obtained in the period immediately after the P2P implementation. The total accident reduction was approximately 32% and, consistent with speed effects, Safety Tutor effectiveness decreased over time. Other ancillary benefits associated with the same A56 devices have been estimated by Cascetta et al. (2010), Cascetta et al. (2011), and Montella et al. (2015a), whose results suggested that they produced significant reduction in fuel consumption of 387.9 tonnes per year, improvements in peak period traffic flow through reduced bottlenecking, and reductions in the standard deviation of average speed from 16.5 km/h to 12.2 km/h (-26%), respectively. An additional contribution was provided by Montella et al. (2012)

that estimated a total accident reduction of 31.2%, with a decreasing pattern over time (-39.4% in the first semester versus -18.7% in the fifth) in an 80 km Safety Tutor sector of the A1 Milano-Napoli motorway (activated on July 1, 2007) analysed from 2001 to 2009.

Since those studies evaluates the effectiveness of some specific Safety Tutor sites in unique contexts, this paper also aims at checking whether findings at national level are robust with respect to previous evaluations.

3. Data

Bounded by availability of data, we test the effectiveness of Safety Tutor in reducing highway vehicle accidents by estimating an econometric model using a unique 15-year panel dataset (2001-2015) that allows us to observe the trend in accident rates 5 years before the Safety Tutor implementation and 5 years after its temporary maximum coverage, reached in 2011[1].

Hence, for each of the 56 motorway sectors, we collected AISCAT (Associazione Italiana Società Concessionarie Autostrade e Trafori, the concessionaires' association) data on the annual number of total highway vehicle accidents (*ACCIDENTS*), the annual number of injured people (*INJURED*), the annual number of fatalities (*FATALITIES*) caused by vehicle accidents, the annual number of accidents involving only light vehicles (*LIGHT*), and the annual number of accidents involving only heavy vehicles (*HEAVY*), as dependent variables. Moreover, we collected data on the annual average daily number of effective vehicles passing through each motorway sector (*DAILY_TRAFFIC*), classified between light (*DAILY_TRAFFIC_LIGHT*) and heavy (*DAILY_TRAFFIC_HEAVY*) vehicles, and data on the annual mileage extension (in kilometres) of each motorway sector (*HIGHWAY_LENGTH*).

Then, we collected ASPI (Autostrade per l'Italia) data to compute the related number of kilometres of motorway sectors covered by the Safety Tutor sites as of 31 December each year (*TUTOR_LENGTH*). Our main explanatory variable, *COVERAGE*, is computed as the ratio between the *TUTOR_LENGTH* and *HIGHWAY_LENGTH* variables. Finally, we collected Global Health Observatory data on the annual alcohol consumption per capita (*ALCOHOL_PC*) in litres and ISPRA (Istituto superiore per la protezione e la ricerca ambientale) data on the annual average age of vehicles (*VEHICLES_AGE*) in years as control variables. For the period of analysis, Table 1 shows the main descriptive statistics for the collected data.

It must be noted that since data concerning *TUTOR_LENGTH* are divided between the number of kilometres covered by Safety Tutor in one carriageway from those covered in the other one, while data concerning highway accidents and traffic are aggregated for the two carriageways, we considered a motorway kilometre treated by the device if it was covered in at least one of the two

[1] New Safety Tutor sites have been activated in 2016.

Table 1: Descriptive statistics of variables of interest (833 Obs.). See Appendix Table A for detailed variable definitions and sources

Variable	Mean	Std. Dev.	Min	Max
ACCIDENTS	155.972	157.659	0.000	915.000
INJURED	266.299	286.867	0.000	1 734.000
FATALITIES	6.739	8.251	0.000	55.000
LIGHT	125.446	123.807	0.000	751.000
HEAVY	30.527	37.328	0.000	237.000
DAILY_TRAFFIC	99 710.070	78 785.180	0.000	301 600.000
DAILY_TRAFFIC_LIGHT	80 232.050	63 996.830	0.000	254 097.000
DAILY_TRAFFIC_HEAVY	19 478.020	16 734.900	0.000	75 528.000
HIGHWAY_LENGTH	98.732	64.441	5.800	273.000
TUTOR_LENGTH	15.410	40.420	0.000	225.100
COVERAGE	0.114	0.246	0.000	1.000
ALCOHOL_PC	8.013	1.001	6.100	9.690
VEHICLES_AGE	8.617	0.851	7.900	10.760

carriageways (see Appendix Table B for progressive deployment of Safety Tutor sites by year).

Finally, to avoid an overly unbalanced panel dataset, we excluded from our dataset Tangenziale esterna di Milano (TEEM) and Milano-Brescia (Bre.Be.Mi), which are motorway sectors that started their operations in 2014 and 2015, respectively. Table 2 summarizes by year the main aggregate data of the unique panel dataset.

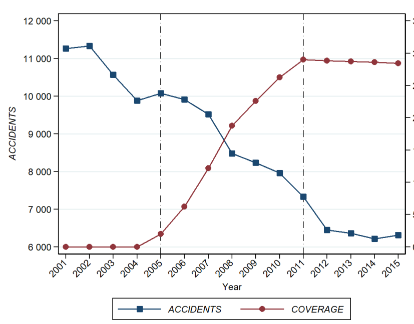
4. Patterns in Italian highway vehicle accidents

For the time period 2001-2015, Figures 1a–1e plot the decreasing trends for all accident categories analysed against *COVERAGE* growth. They show that the number of total accidents, injuries, fatalities, and light and heavy accidents experienced a decreasing trend both before the first Safety Tutor installation in 2005 and after its temporary maximum coverage that was reached in 2011. These phenomena suggest the need to disentangle the Safety Tutor effect from other key factors to explain reductions in accident categories.

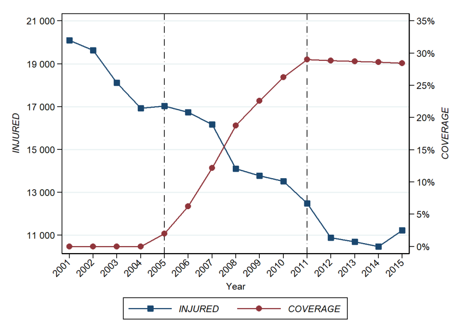
Figures 2a–2e plot annual rates for the five accident categories as measured by their absolute values over the average daily number of effective vehicles, rescaled by 1 000. In each graph, trends are divided between two subsamples: the first includes annual accident rates for those 33 motorway sectors free of any Safety Tutor technology for the overall period of analysis; the second includes annual accident rates for the remaining 23 motorway sectors that installed at least one Safety Tutor site from 2005 onwards (See Appendix Table C for the detailed list of motorway sectors).

A brief analysis reveals the following patterns: rates have fallen over time for all the accident categories under examination; however, they are higher in those motorway sectors that decided to adopt the safety device (with the exception of Figure 2c where *FATALITIES* rates shift between the two subsamples at the

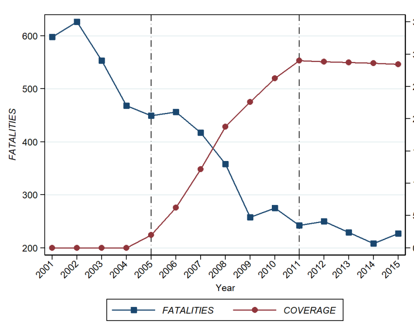
Figure 1: Accident category trends versus *COVERAGE*, 2001-2015



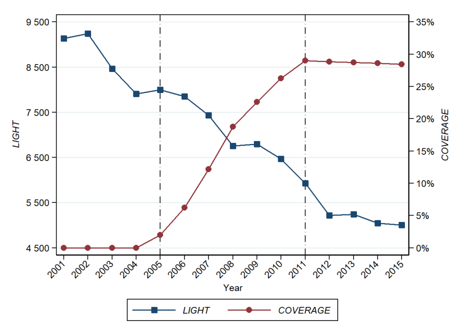
(a) *ACCIDENTS* vs *COVERAGE*



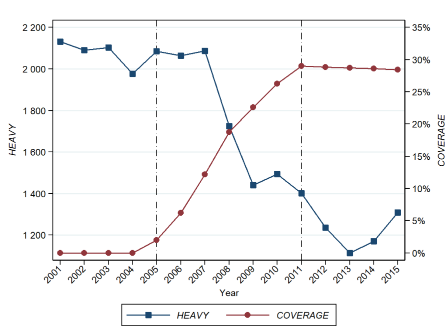
(b) *INJURED* vs *COVERAGE*



(c) *FATALITIES* vs *COVERAGE*

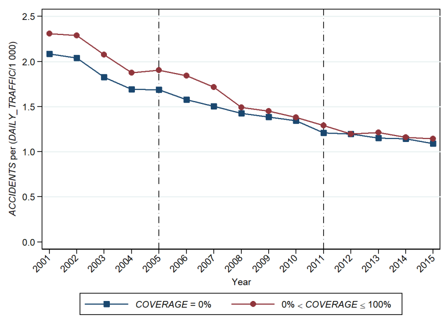


(d) *LIGHT* vs *COVERAGE*

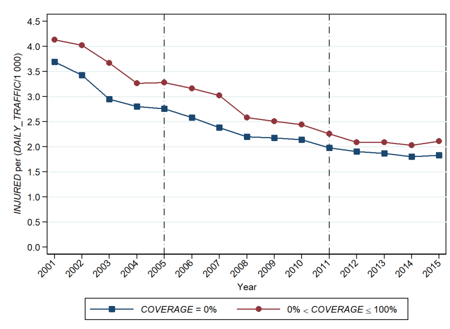


(e) *HEAVY* vs *COVERAGE*

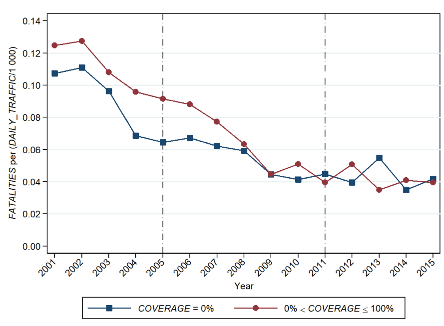
Figure 2: Accident category rates for motorway sectors covered by at least one Safety Tutor site versus accident category rates for motorway sectors not covered by the device, 2001-2015



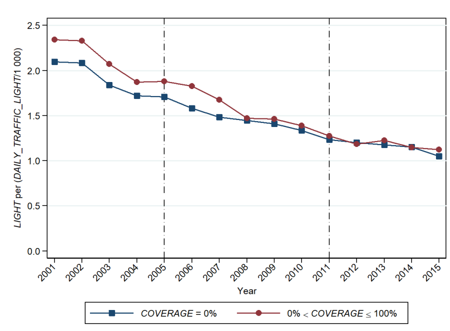
(a) *ACCIDENTS* rates



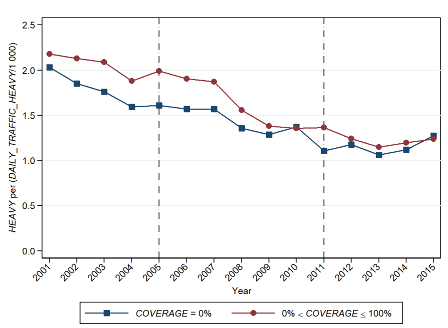
(b) *INJURED* rates



(c) *FATALITIES* rates



(d) *LIGHT* rates



(e) *HEAVY* rates

Table 2: Aggregate data for analysis, 2001-2015. *COVERAGE* is given by the ratio between *TUTOR_LENGTH* and *HIGHWAY_LENGTH*

Year	*ACCIDENTS*	*INJURED*	*FATALITIES*	*LIGHT*	*HEAVY*	*LENGTH*		*COVERAGE*
						HIGHWAY	*TUTOR*	
2001	11 265	20 087	598	9 134	2 131	5 387.9	0.0	0.0%
2002	11 334	19 624	626	9 243	2 091	5 387.9	0.0	0.0%
2003	10 568	18 117	553	8 465	2 103	5 387.9	0.0	0.0%
2004	9 889	16 919	468	7 912	1 977	5 391.2	0.0	0.0%
2005	10 081	17 038	449	7 996	2 085	5 432.4	107.2	2.0%
2006	9 915	16 735	456	7 851	2 064	5 441.1	339.4	6.2%
2007	9 523	16 172	417	7 435	2 088	5 446.4	664.3	12.2%
2008	8 482	14 100	358	6 757	1 725	5 485.9	1 028.0	18.7%
2009	8 234	13 766	258	6 793	1 441	5 485.9	1 239.8	22.6%
2010	7 964	13 521	275	6 471	1 493	5 523.2	1 450.9	26.3%
2011	7 332	12 480	242	5 931	1 401	5 523.4	1 602.0	29.0%
2012	6 450	10 881	250	5 214	1 236	5 548.6	1 602.0	28.9%
2013	6 360	10 696	229	5 246	1 114	5 573.5	1 602.0	28.7%
2014	6 218	10 472	208	5 047	1 171	5 598.1	1 602.0	28.6%
2015	6 310	11 219	227	5 001	1 309	5 630.7	1 602.0	28.5%

Table 3: Maximums, minimums, and percentage changes by accident category rates. % Δ identifies the percentage change between the 2001 and 2015 rates. Negative numbers indicate downward trends over time. The number in parentheses represents the year of occurrence

Annual rates	*COVERAGE* = 0%			0% < *COVERAGE* ≤ 100%		
	Max	Min	% Δ	Max	Min	% Δ
ACCIDENTS	2.09 (2001)	1.09 (2015)	-47.6	2.31 (2001)	1.15 (2015)	-50.4
INJURED	3.69 (2001)	1.80 (2014)	-50.4	4.13 (2001)	2.03 (2014)	-48.9
FATALITIES	0.11 (2002)	0.03 (2014)	-60.9	0.13 (2002)	0.04 (2013)	-68.3
LIGHT	2.10 (2001)	1.05 (2015)	-49.9	2.34 (2001)	1.13 (2015)	-51.9
HEAVY	2.03 (2001)	1.06 (2013)	-37.3	2.18 (2001)	1.15 (2013)	-43.2

end of period). This phenomena suggests that Safety Tutor sites have been first activated along those motorway sectors characterized by higher accident and mortality rates, as confirmed by Falsi (2009). Therefore, to estimate the Safety Tutor effect, unobserved heterogeneity due to reverse causality is a clear issue.

Descriptive statistics summarizing trends in accident categories rates are presented in Table 3. Although all rates tend to converge to the same values at the end of the period, the difference in the 2001-2015 percentage change between the two subgroups for each category is not clear. Motorway sectors covered by at least one Safety Tutor site experienced an additional reduction in *FATALITIES* rates (-7.4%), *HEAVY* rates (-5.9%), *ACCIDENTS* rates (-2.8%), and *LIGHT* rates (-2.0%) and an increase in *INJURED* rates (1.5%) with respect to the percentage changes of the motorway sectors free of the device. At first sight, the possible effect of Safety Tutor seems sensibly lower with respect to the encouraging results obtained by previous studies summarized in Section 2. Thus, confounding factors for explaining highway accident reduction should be eliminated to provide a reliable evaluation.

5. Methodology

The aim of this paper is primarily to investigate whether average speed enforcement efforts affect highway safety; therefore, the model presented to explain highway accidents makes such efforts. However, as suggested by Welki and Zlatoper (2007, 2009), the model should contain other determinants that may explain the phenomena to minimize the estimation bias from omitted factors. Highway vehicle accidents depend, among other things, on traffic and congestion, economic conditions, territory and driver characteristics, concessionaires' management, and government regulations. In our model, we decide to limit these factors, as in the following Equation 1:

$$\begin{aligned}\text{Vehicle accidents} = f\,(&\text{enforcement efforts, traffic intensity,}\\ &\text{economic conditions, driver characteristics,}\\ &\text{road management, other factors)}\end{aligned} \tag{1}$$

where $COVERAGE$ is our main explanatory variable depicting the enforcement efforts. Considering that exposure to dangerous driving situations increases with the volume of vehicles (Loeb et al., 1994), we control for congestion and traffic intensity using the empirical measure of the average daily number of effective vehicles passing through each motorway sector ($DAILY\_TRAFFIC$, $DAILY\_TRAFFIC\_LIGHT$, and $DAILY\_TRAFFIC\_HEAVY$). Economic conditions (that are also correlated with the amount of driving activity) are represented by the annual average age of vehicles ($VEHICLES\_AGE$) at a national level as a proxy for the technological development of vehicles. Moreover, considering that greater alcohol consumption is assumed to be correlated with the alcohol consumption of drivers (Loeb et al., 1994), we control for that particular driver characteristic through the annual per capita ethanol consumption (in litres) for all beverages ($ALCOHOL\_PC$) at a national level as a measure of alcoholic intoxication while driving.

The panel structure of our dataset allows us to control for possibly correlated, time-invariant heterogeneity without observing it. In particular, motorway sector fixed effects capture morphological and atmospheric characteristics of the territory (including the consequent speed limits), the different driving behaviour between areas, and the presence of additional speed management programmes (e.g., fixed speed cameras). Furthermore, as underlined in Section 1, this analysis takes into account the motorway network under concession. As studied by Albalate (2011) and Percoco (2016) in other contexts, different toll fares applied by the 24 licensee companies (and their resulting different economic outcomes) can directly affect the level of road quality and maintenance investments, which in turn can affect accident rates. Considering that for the period of analysis, all motorway sectors were managed by the same companies[2], the time-invariant

[2] In 2009 the Società Autostrade di Venezia e Padova S.p.A. was absorbed by Concessioni Autostradali Venete (C.A.V.) S.p.A. concurrent with the opening of the new Passante di Mestre motorway sector.

component of the "road management" effect is captured by motorway dummies as well.

From the time trend perspective, year dummies allow us to capture other confounding factors not explicitly included in the model that contribute to the decreasing trend of accident rates, such as the common improvement of highways (e.g., ameliorated motorway paving) and the technological development of vehicles (e.g., assisted braking and safety systems). Moreover, three government regulations are accounted for through time fixed effects: first, the introduction of a penalty-point system for driving licensees in 2003 (Gazzetta Ufficiale, 2003); second, the introduction of the "Decreto Bianchi" in 2007 (Gazzetta Ufficiale, 2007), which strengthened the penalties for road traffic offences (e.g., excess speed, driving under the influence of alcohol and drugs, driving while using a cell phone) and limited the maximum speed (80 km/h) and maximum specific power of cars (50 kilowatts/ton) for first year drivers; and third, the introduction in 2010 of the obligation that vehicles travelling on highways adopt winter tyres or keep snow chains on board during winter months (Gazzetta Ufficiale, 2010).

Turning to the importance of unit and time fixed effects, Figure 3 shows the heterogeneity across motorway sectors by plotting the average *ACCIDENTS* rates over the average *COVERAGE* for each motorway sector during the period of analysis (where the average sectors treated by Safety Tutor are among those motorways with the highest average accident rates), while Figure 4 shows how time plays a fundamental role in explaining accident reduction by plotting the average *ACCIDENTS* rates for each year (see Appendix Figures A–B for the same graphs related to *INJURED*, *FATALITIES*, *LIGHT*, and *HEAVY* rates).

To empirically test the effectiveness of Safety Tutor in reducing highway vehicle accidents, we used a semi-log model by regressing the following panel equation:

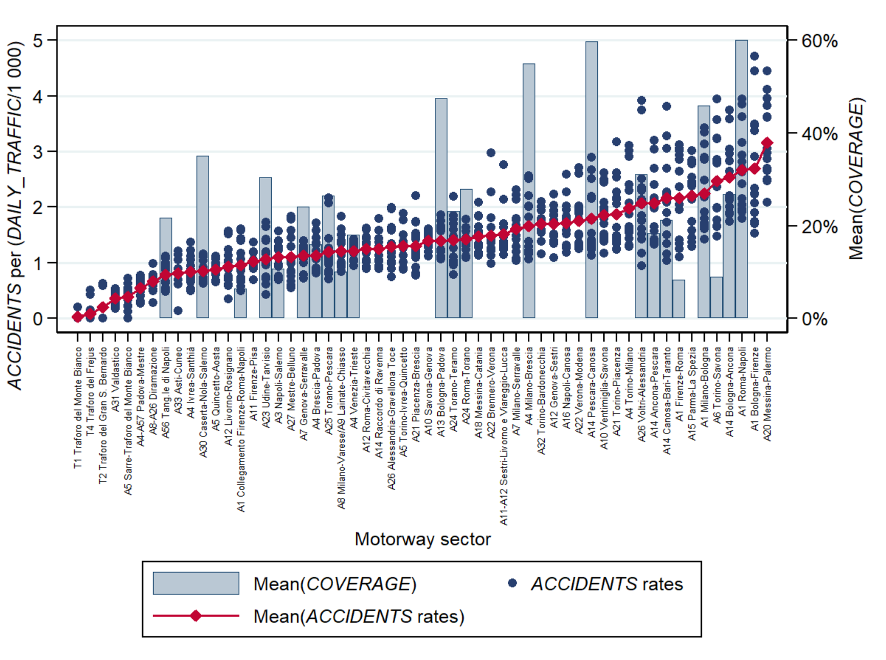
$$\log\left(\frac{Y+1}{DAILY\_TRAFFIC} \times 10\,000\right)_{it} = \beta_0 + \\ + \beta_1 COVERAGE_{it-1} + b'X_t + \alpha_i + \delta_t + \epsilon_{it} \quad (2)$$

where the dependent variables are given by the logarithm of Y (the set of our variables of interest *ACCIDENTS*, *INJURED*, *FATALITIES*, *LIGHT*, and *HEAVY*) plus 1, weighted by the average daily number of effective vehicles (*DAILY_TRAFFIC*[3]), and rescaled by 10 000. X_t is a 2-dimensional vector of control variables (*VEHICLES_AGE* and *ALCOHOL_PC*), α_i and δ_t are motorway sector and year fixed effects, respectively, and ϵ_{it} is the error term.

Considering that Safety Tutor installation took place in different periods during the course of each year, we lagged the main explanatory variable by one period to ensure our dependent variables were regressed with respect to

[3]The *LIGHT* and *HEAVY* variables are coherently weighted by *DAILY_TRAFFIC_LIGHT* and *DAILY_TRAFFIC_HEAVY*, respectively.

Figure 3: Heterogeneity of *ACCIDENTS* rates across motorway sectors



full annual *COVERAGE*. Since some motorway sectors belong to the same highway, heteroskedasticity- and autocorrelation-consistent standard errors are computed by clustering sectors at the highway level. To simplify the notation of our dependent variables in the next sections, we will use the following labels: $\log(ACCIDENTS)$, $\log(INJURED)$, $\log(FATALITIES)$, $\log(LIGHT)$, $\log(HEAVY)$. Table 4 shows the main descriptive statistics of our dependent variables.

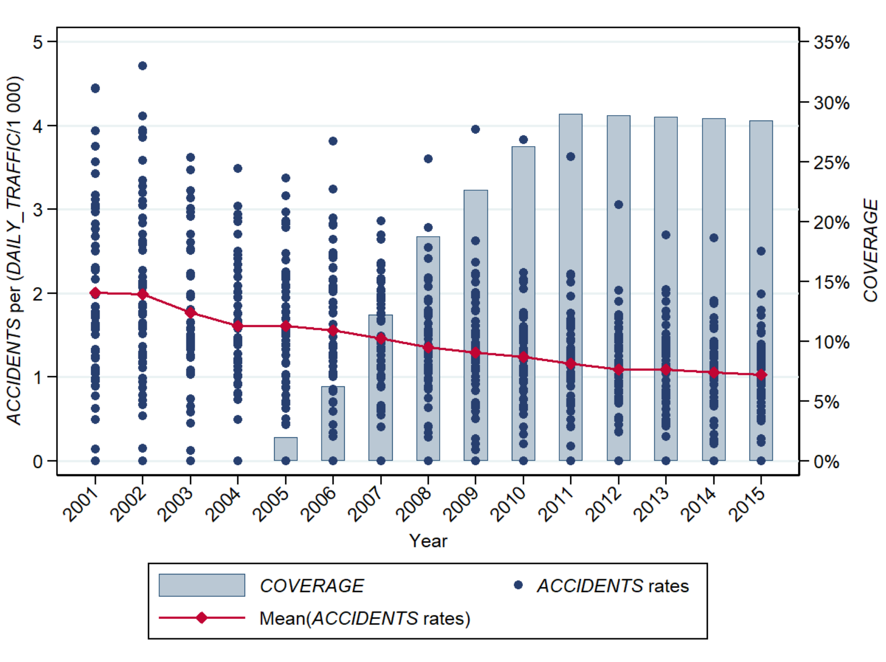
Table 4: Summary statistics of dependent variables (832 Obs.)

Variable	Mean	Std. Dev.	Min	Max
$\log(ACCIDENTS)$	2.522	0.601	0.074	3.855
$\log(INJURED)$	2.976	0.715	0.744	5.118
$\log(FATALITIES)$	-0.301	0.812	-2.717	1.862
$\log(LIGHT)$	2.556	0.571	0.356	3.890
$\log(HEAVY)$	2.522	0.693	-0.676	4.756

6. OLS Estimation Results

For each accident category under analysis, Tables 5–9 report the results from four different semi-log specifications of Equation 2, estimated by OLS

Figure 4: Heterogeneity of *ACCIDENTS* rates across years



regressions. Model (1) is a pooled OLS estimation, Model (2) adds motorway sector fixed effects, Model (3) includes our set of control variables, and Model (4) includes time dummies.

Table 5 reports a possible relationship between Safety Tutor coverage and total highway vehicle accident reduction. Model (1), the most parsimonious specification, shows a small positive (and counterintuitive) correlation between the number of accidents and the presence of Safety Tutor sites, but it is not significant. Once we control for those different time-invariant factors that can directly affect accidents across motorway sectors, Model (2) estimates a negative and significant correlation, showing that a 10% increase in Safety Tutor coverage could on average reduce highway vehicle accidents by 4.6%. The coefficient becomes significantly lower (-0.202) once we include in the regression our set of controls (Model 3). Consistent with conventional wisdom as well as findings reported in previous studies (Loeb et al., 1994), the $ALCOHOL\_PC$ coefficient is positive and significant, as greater alcohol consumption leads to more highway accidents. As concerns $VEHICLES\_AGE$, its estimation is inversely related to vehicle accidents, probably because weaker economic circumstances (correlated with ageing vehicles) should lead to the diminished use of cars and trucks. Moreover, the greater difficulty older motor vehicles have reaching high speeds can lead to a reduction in highway accidents.

The $COVERAGE_{t-1}$ coefficient becomes lower and less significant when

Table 5: OLS regressions of log ($ACCIDENTS$). Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

Dependent variable	log ($ACCIDENTS$)			
	(1)	(2)	(3)	(4)
$COVERAGE_{t-1}$	0.0511	-0.617***	-0.202***	-0.138**
	(0.149)	(0.0652)	(0.0583)	(0.0586)
$ALCOHOL\_PC$			0.125***	
			(0.0169)	
$VEHICLES\_AGE$			-0.0535***	
			(0.0162)	
Motorway sector	No	Yes	Yes	Yes
Year	No	No	No	Yes
Constant	2.493***	2.564***	2.000***	2.843***
	(0.0943)	(0.00695)	(0.240)	(0.0318)
Observations	777	777	777	777
R^2	0.000	0.165	0.412	0.463

we add year dummies to the explanatory variables, as can be seen in Model (4). The model shows that a 10% increase in Safety Tutor coverage could on average reduce highway vehicle accidents by 1.3%. This result has a direct interpretation: time plays a fundamental role in explaining the reduction in accidents, as it captures either some sort of technological improvement effect (e.g., technical progress of road surface maintenance and innovation of vehicle safety systems) or a less plausible enhancement of driving behaviour. Hence, year dummies appear as relevant omitted variables because the point estimate decreases without leading the standard error to increase as well. Considering that motorway sector and year fixed effects appear to explain a large part of the variability (as confirmed by an R^2 comparison between specifications), Model (4) is the one that best fits our data.

Table 6 reports a possible relationship between Safety Tutor coverage and the number of people injured by vehicle accidents. Estimations of the four models present a very similar path, as expected. Focusing just on Model (4), the $COVERAGE_{t-1}$ coefficient shows that a 10% increase in Safety Tutor coverage could, on average, reduce injuries by 1.0%.

Table 7 correlates Safety Tutor coverage with the number of fatalities. For all specifications, the estimated coefficients emphasize that this technology has a significant and stronger impact on reducing deaths than on reducing total accidents and injuries. In particular, Model (4) shows that a 10% increase in Safety Tutor coverage could on average reduce fatalities by 3.6%. Our interpretation is straightforward: traffic, congestion, and the dangerousness of some highway sectors (which are among the prominent factors causing vehicle accidents) are not reduced by Safety Tutor technology, but the plausible decrease in the average speed enforced by the point-to-point speed control system (together with the technological improvement of vehicles) could have reduced the severity of

Table 6: OLS regressions of $\log(INJURED)$. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

Dependent variable	$\log(INJURED)$			
	(1)	(2)	(3)	(4)
$COVERAGE_{t-1}$	0.219	-0.609***	-0.184***	-0.108*
	(0.175)	(0.0724)	(0.0630)	(0.0597)
$ALCOHOL\_PC$			0.125***	
			(0.0171)	
$VEHICLES\_AGE$			-0.0583***	
			(0.0172)	
Motorway sector	No	Yes	Yes	Yes
Year	No	No	No	Yes
Constant	2.929***	3.017***	2.491***	3.338***
	(0.112)	(0.00772)	(0.254)	(0.0400)
Observations	777	777	777	777
R^2	0.006	0.135	0.353	0.421

vehicle accidents. Nevertheless, this model fits the data worse than the previous ones, as the R^2 shows.

Table 7: OLS regressions of $\log(FATALITIES)$. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

Dependent variable	$\log(FATALITIES)$			
	(1)	(2)	(3)	(4)
$COVERAGE_{t-1}$	-0.534**	-1.088***	-0.523***	-0.440***
	(0.230)	(0.108)	(0.124)	(0.139)
$ALCOHOL\_PC$			0.247***	
			(0.0341)	
$VEHICLES\_AGE$			0.0144	
			(0.0361)	
Motorway sector	No	Yes	Yes	Yes
Year	No	No	No	Yes
Constant	-0.277***	-0.218***	-2.351***	0.238***
	(0.0940)	(0.0115)	(0.503)	(0.0596)
Observations	777	777	777	777
R^2	0.025	0.127	0.254	0.289

Tables 8–9 focus on the correlation between Safety Tutor coverage and total light or heavy vehicle accidents, respectively. While estimated results explaining light vehicle accident reduction are very similar to those explaining total accidents and injuries, the Model (3) and Model (4) $COVERAGE_{t-1}$ coefficients explaining heavy vehicle accident reduction are smaller and not significant. Considering that the average speed of trucks is already lower with respect to the highway speed limit, it is plausible to expect no significant effect of the Safety

Table 8: OLS regressions of $\log(LIGHT)$. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

Dependent variable	$\log(LIGHT)$			
	(1)	(2)	(3)	(4)
$COVERAGE_{t-1}$	-0.0162	-0.639***	-0.208***	-0.151**
	(0.141)	(0.0644)	(0.0593)	(0.0589)
$ALCOHOL\_PC$			0.125***	
			(0.0190)	
$VEHICLES\_AGE$			-0.0610***	
			(0.0168)	
Motorway sector	No	Yes	Yes	Yes
Year	No	No	No	Yes
Constant	2.534***	2.600***	2.099***	2.878***
	(0.0871)	(0.00686)	(0.261)	(0.0400)
Observations	777	777	777	777
R^2	0.000	0.168	0.422	0.468

Tutor device on improving heavy vehicle drivers' safety. These results coherently support the interpretation previously given to *FATALITIES* estimations.

Table 9: OLS regressions of $\log(HEAVY)$. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

Dependent variable	$\log(HEAVY)$			
	(1)	(2)	(3)	(4)
$COVERAGE_{t-1}$	0.0278	-0.527***	-0.127	-0.0367
	(0.182)	(0.0966)	(0.102)	(0.104)
$ALCOHOL\_PC$			0.117***	
			(0.0282)	
$VEHICLES\_AGE$			-0.0551**	
			(0.0213)	
Motorway sector	No	Yes	Yes	Yes
Year	No	No	No	Yes
Constant	2.498***	2.557***	2.068***	2.821***
	(0.0948)	(0.0103)	(0.340)	(0.0685)
Observations	777	777	777	777
R^2	0.000	0.052	0.151	0.187

7. IV Estimation Results

In the previous section, we identified a positive correlation between Safety Tutor and an average reduction for 4 out of the 5 accident categories analysed. Although the panel structure of our dataset eliminated many unobserved factors, OLS estimates might be still biased because of additional omitted variables and reverse causality issues. Highway accidents are complex events that involve a variety of human responses to external stimuli (Elvik, 2006; Ayyildiz et al., 2017), as well as complex interactions between vehicles (Dadashova et al., 2014), roadway characteristics, traffic-related factors, and environmental conditions (Amin et al., 2014; Bardal and Jørgensen, 2017).

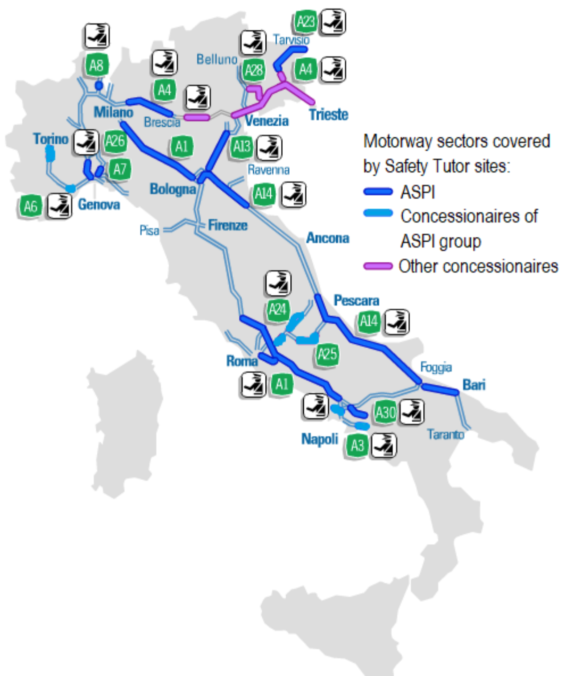
Naturally, it is impossible to control for all possible variables that might be correlated with highway accidents, such as drivers' skills, temporary roadworks, police enforcement, weather and lighting conditions. For instance, the unobserved age of drivers and the quality of health care can affect the severity of injuries and the number of fatalities due to vehicle accidents. Most importantly, if those unobserved factors are correlated with observed factors, biased parameters will be estimated, and incorrect inferences could be drawn (Mannering and Bhat, 2014; Mannering et al., 2016). As concerns reverse causality, Safety Tutor sites were first activated along those motorway sectors characterized by higher accident and mortality rates (Falsi, 2009), as confirmed by Figure 2 in Section 3. For this issue, the practice of lagging the main explanatory variable to control possible simultaneous causation does not solve the problem (Reed, 2015).

To address these identification issues, we utilize an instrumental variable strategy by exploiting the membership of some motorway sectors in the Autostrade per l'Italia (ASPI) group as an instrument for $COVERAGE$. The motivation is straightforward: ASPI (the major highway concessionaire) and the Italian traffic police developed the Safety Tutor technology in 2004 (Autostrade per l'Italia, 2016); therefore, it is more likely that the device was first installed on those motorway sectors managed by the company itself or by other concessionaires under its control. Between 2005 and 2010 (i.e., the period where the majority of Safety Tutor installation took place), ASPI controlled Tangenziale di Napoli S.p.A. (100%), Autostrada Torino-Savona S.p.A. (99.9%), Società Autostrada Tirrenica S.p.A. (93.7%), Strada dei Parchi S.p.A. (60.0%), Autostrade Meridionali S.p.A. (58.9%), and Società Italiana per il Traforo del Monte Bianco S.p.A. (51.0%), which in turn controlled the 58.0% of Raccordo Autostradale Valle d'Aosta S.p.A. (Autostrade per l'Italia, 2006, 2011) [4].

Indeed, if we focus on the geographical exposure of $COVERAGE$, Figure 5 shows the location of Safety Tutor sites in 2015. Hence, it is clear that being part of ASPI group was a major determinant for the adoption of Safety Tutor, as it tends to concentrate along those motorway sectors managed by ASPI and its controlled concessionaires. As Table 10 describes, in 2011 (that is, when Safety Tutor reached its maximum coverage during the period of analysis) 1 450.3 out of 1 602.0 kilometres of Safety Tutor sites (90.5%) were installed within ASPI group.

[4] In 2011, Autostrada Torino-Savona S.p.A., Società Autostrada Tirrenica S.p.A., and Strada dei Parchi S.p.A. were no longer members of ASPI group (Autostrade per l'Italia, 2012).

Figure 5: Safety Tutor sites in 2015, formatted by authors



Consequently, our instrument is given by the following equation:

$$INSTRUMENT = TECHNOLOGY \times ASPI\_GROUP \tag{3}$$

where *TECHNOLOGY* is a dummy variable equal to 1 (mean = 0.736, standard deviation = 0.441) for those observations from 2005 onwards (i.e., when the Safety Tutor technology was available), and *ASPI_GROUP* is another dummy variable equal to 1 (mean = 0.612, standard deviation = 0.488) for those motorway sectors managed by Autostrade per l'Italia and its controlled concessionaires. Considering that in Equation 2, we regressed the lagged value of the main explanatory variable, our identification strategy is to use the lagged value of this iteration (mean = 0.449, standard deviation = 0.498) as an instrument for $COVERAGE_{t-1}$.

To exploit this variation to estimate causal relationships, our instrument needs to respect three main assumptions (Angrist et al., 1996). First, there might be a correlation between the instrument and the endogenous variable. Since there is a strong relationship between those motorway sectors managed by ASPI group and Safety Tutor adoption (1$^{\text{st}}$ Stage F-statistic = 25.06), as discussed above, the *relevance* assumption is satisfied.

Second, the *exclusion* restriction implied by our instrumental variable regression states that, conditional on the controls included in the regression, the

Table 10: Progressive deployment of Safety Tutor sites by concessionaires, 2005-2011

Concessionaires	*TUTOR_LENGTH*						
	2005	2006	2007	2008	2009	2010	2011
ASPI[1]	107.2	339.4	543.1	869.6	1 072.0	1 240.2	1 276.8
TANG.NAPOLI[2]	0.0	0.0	0.0	0.0	9.4	9.4	9.4
TORINO-SAVONA[3]	0.0	0.0	0.0	0.0	0.0	29.2	29.2
SAT[4]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AUT.PARCHI[5]	0.0	0.0	121.2	121.2	121.2	121.2	121.2
AUT.MERIDIONALI[6]	0.0	0.0	0.0	0.0	0.0	13.7	13.7
SITMB[7]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RAV[8]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total *ASPI_GROUP* (A)	107.2	339.4	664.3	990.8	1 202.6	1 413.7	1 450.3
AUTOVIE_VENETE [9]	0.0	0.0	0.0	0.0	0.0	0.0	104.1
BRESCIA-PADOVA [10]	0.0	0.0	0.0	37.2	37.2	37.2	47.6
Total *OTHERS* (B)	0.0	0.0	0.0	37.2	37.2	37.2	151.7
Total (A+B)	107.2	339.4	664.3	1 028.0	1 239.8	1 450.9	1 602.0

Notes: [1] Autostrade per l'Italia S.p.A., [2] Tangenziale di Napoli S.p.A., [3] Autostrada Torino-Savona S.p.A., [4] Società Autostrada Tirrenica S.p.A., [5] Strada dei Parchi S.p.A., [6] Autostrade Meridionali S.p.A., [7] Società Italiana per il Traforo del Monte Bianco S.p.A., [8] Raccordo Autostradale Valle d'Aosta S.p.A., [9] Autovie Venete S.p.A., [10] Autostrada Brescia-Verona-Vicenza-Padova S.p.A.

membership in ASPI group has no direct effect on highway accident categories other than its effect through *COVERAGE* (that is, the instrument must not be correlated with any other unobservable determinant of the dependent variable). The major concern here is that concessionaires within ASPI group might affect accident rates through different maintenance programmes or investment policies. However, the motorway sectors' concessionaires do not change over the period of analysis; thus, their time-invariant differences are captured by fixed effects. Moreover, in the road safety literature, accidents always depend mainly on speed and traffic volume (Aarts and Van Schagen, 2006; Hauer, 2009). Considering that speed limits are enforced by the traffic police and that congestion variables are included in our specification, there is little that concessionaires can do on their own to reduce accidents (Ragazzi, 2006). For these reasons, we believe that the *exclusion* restriction is satisfied as well.

Third, the *independence* assumption requires that our instrument is assigned to observations independently of their potential outcomes and treatments; in other words, that ASPI group membership is as good as randomly assigned to motorway sectors. In our application, it is clear that the decision to assign the management of a motorway sector to a particular concessionaire does not appear to be random. However, assignment occurred mainly between the 1960s and 1970s (Bank of Italy, 2015), and hence many decades before the idea of developing an average speed enforcement system to improve drivers' safety. Therefore, we can assume that ASPI group membership is independent of the volume of highway accidents occurring during the period of analysis.

Finally, Safety Tutor exposure is not homogeneous across motorway sectors, as the percentage of kilometres covered by the device varies across sectors and years (see Appendix Table B for the progressive deployment of Safety Tutor sites for each motorway sector by year). Thus, to estimate a causal effect of *COVERAGE* on reducing highway accidents, our instrumental variable needs to also satisfy a fourth condition, namely the *monotonicity* assumption (Imbens and Angrist, 1994): if a particular motorway sector becomes a member of ASPI group and increases its Safety Tutor coverage, then this change must not decrease the Safety Tutor coverage of any other motorway sector. In other words, it means that a certain instrument may induce treatment for some observations but not for others, but it cannot induce treatment for some and simultaneously induce non-treatment for others.

Considering that the last assumption is also satisfied, our IV estimator is interpretable as a weighted local average treatment effect; hence, it captures the causal effect of *COVERAGE* only for those "complier" motorway sectors that decided to install or to increase Safety Tutor adoption because they are members of ASPI group (i.e., those that respond to the exogenous "shift" in the endogenous variable induced by the instrument).

Two-stage least squares estimates of Model (4) (which includes both motorway sector and year fixed effects) for all five accident categories of interest are presented in Table 11, where *COVERAGE* is treated as endogenous. If we focus on the *relevance* condition, Panel B displays the strong first-stage relationship between the lagged value of *COVERAGE* and the lagged value of *INSTRUMENT*. It is positive and significant, and it basically predicts the expected value of Safety Tutor exposure based on the instrument. Therefore, the motorway sectors of ASPI group have an average *COVERAGE* of 21.1%. As regards the Panel C results, point estimates of the reduced form regressions of the outcome variables over the instrument are close to zero and not significant for all of our specifications. Thus, there is no evidence of an "intention-to-treat" (ITT) effect (that is, to be a member of ASPI group does not itself affect highway accidents). Reasonably, the corresponding 2SLS results (Panel A) that depict the impact of Safety Tutor are also not significant. With the exception of Column (3), the point estimates are significantly larger than the OLS estimates reported in Panel D. This may be due to attenuation biases induced by measurement error [5] in the *COVERAGE* variable and to a plausible spillover effect of Safety Tutor sites on other motorway sectors free of the technology. However, standard errors are almost five times larger than OLS as well; therefore, the estimates are barely not significant (p-value of Column (1) = 0.12). The IV results suggest that there is no clear evidence of a significant causal effect of Safety Tutor on preventing highway accidents in any of the categories analysed,

[5] Here, we are referring to "measurement error" broadly construed because we are considering a motorway kilometre treated by Safety Tutor if it is covered by the device in at least one of the two carriageways (as explained in Section 3). In reality, few motorway sectors have a slight different $TUTOR\_LENGTH$ between the two carriageways.

at least for the subgroup of "complier" motorway sectors.

8. Robustness Checks

To ensure that our estimates are not driven by outliers, the following section reports the 2SLS results of Model (4) for all five accident categories of interest using a subsample without peculiar motorway sectors. In particular, we performed the same analysis without considering highway tunnels (T1 Traforo del Monte Bianco, T2 Traforo del Gran S. Bernardo, T4 Traforo del Frejus), the motorway sector with the highest average number of accidents within the period of analysis (A14 Bologna-Ancona), the motorway sector with the highest average Safety Tutor coverage within the period of analysis (A1 Roma-Napoli), and the new motorway sector introduced in 2008 (A33 Asti-Cuneo). Table 12 shows that the 2SLS (Panel A), first stage (Panel B), reduced form (Panel C) and OLS (Panel D) results follow a very similar path; therefore, our previous estimates that include all motorway sectors can be considered consistent.

9. Conclusions

The analysis of highway accident data has long been used as a basis for directing and implementing regulatory policies and enforcement activities designed to improve safety. Therefore, this paper contributes to the vehicle accident analysis literature by accurately testing the effectiveness of Safety Tutor in reducing total accidents, injuries, fatalities, light vehicle accidents, and heavy vehicle accidents on the Italian tolled motorway network during the period 2001-2015.

With respect to previous studies that have focused on the impact of specific Safety Tutor sites in unique contexts, the novel contribution of the paper lies, first, in performing a robust evaluation of this device at the national level by using a unique 15-year panel dataset (which makes it possible to observe the trend in accident rates 5 years before the implementation of Safety Tutor and 5 years after its temporary maximum coverage) and, second, in exploiting the heterogeneity within all motorway sectors (including both those that had installed the device and those that had not). By exploiting the longitudinal structure of our dataset, which allowed us to control for many unobserved factors, OLS regressions identified a positive correlation between the device and highway accident reduction. In particular, a 10% increase in Safety Tutor coverage is associated with an average reduction in total accidents of nearly 1.3%, injuries of 1.0%, fatalities of 3.6%, and light vehicle accidents of 1.4%. However, those results appear considerably lower than previous estimates and far from the 80% mortality rate reduction underlined by Autostrade per l'Italia in 2016. Differences between those findings have a direct interpretation: the larger time span taken into account by our empirical analysis highlights how time plays a fundamental role in explaining accident reduction, as it also captures the general improvement of highways (e.g., ameliorated motorway paving), the technological development of vehicles (e.g., assisted braking and safety systems), and the

Table 11: IV regressions of Model (4) for the five accident categories of interest. Panel A reports 2SLS estimates of the coefficient of interest (β_1 of Equation 2), instrumenting for $COVERAGE_{t-1}$ using $INSTRUMENT_{t-1}$. Panel B reports the corresponding first stage. Panel C reports the reduced form of the dependent variables against $INSTRUMENT_{t-1}$. Panel D reports the previous coefficients from the OLS regressions of Tables 5–9. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

	(1)	(2)	(3)	(4)	(5)
Panel A: *2SLS*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$COVERAGE_{t-1}$	-0.371	-0.340	-0.130	-0.327	-0.464
	(0.239)	(0.237)	(0.501)	(0.267)	(0.515)
R^2	0.446	0.406	0.281	0.459	0.162
Panel B: *1st Stage*	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$
$INSTRUMENT_{t-1}$	0.211***	0.211***	0.211***	0.211***	0.211***
	(0.042)	(0.042)	(0.042)	(0.042)	(0.042)
R^2	0.342	0.342	0.342	0.342	0.342
Panel C: *Reduced Form*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$INSTRUMENT_{t-1}$	-0.0783	-0.0718	-0.0274	-0.0689	-0.0979
	(0.0512)	(0.0498)	(0.109)	(0.0579)	(0.108)
R^2	0.461	0.420	0.274	0.465	0.189
Panel D: *OLS*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$COVERAGE_{t-1}$	-0.138**	-0.108*	-0.440***	-0.151**	-0.0367
	(0.0586)	(0.0597)	(0.139)	(0.0589)	(0.104)
R^2	0.463	0.421	0.289	0.468	0.187
1st Stage F-statistic	25.06	25.06	25.06	25.06	25.06
Motorway sector	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Observations	777	777	777	777	777

Table 12: Robustness checks for IV regressions of Model (4) of the five accident categories of interest. Panel A reports the 2SLS estimates of the coefficient of interest (β_1 of Equation 2), instrumenting for $COVERAGE_{t-1}$ using $INSTRUMENT_{t-1}$. Panel B reports the corresponding first stage. Panel C reports the reduced form of the dependent variables against $INSTRUMENT_{t-1}$. Panel D reports the OLS estimates of the dependent variables against $COVERAGE_{t-1}$. Clustered standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control for motorway sector and year is as indicated

	(1)	(2)	(3)	(4)	(5)
Panel A: *2SLS*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$COVERAGE_{t-1}$	-0.370	-0.377	0.176	-0.359	-0.205
	(0.283)	(0.283)	(0.539)	(0.321)	(0.550)
R^2	0.511	0.440	0.269	0.486	0.205
Panel B: *1st Stage*	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$	$COVERAGE_{t-1}$
$INSTRUMENT_{t-1}$	0.194***	0.194***	0.194***	0.194***	0.194***
	0.0397	0.0397	0.0397	0.0397	0.0397
R^2	0.338	0.338	0.338	0.338	0.338
Panel C: *Reduced Form*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$INSTRUMENT_{t-1}$	-0.0717	-0.0732	0.0340	-0.0697	-0.0398
	(0.0528)	(0.0523)	(0.107)	(0.0615)	(0.107)
R^2	0.529	0.459	0.282	0.498	0.211
Panel D: *OLS*	$\log(ACCIDENTS)$	$\log(INJURED)$	$\log(FATALITIES)$	$\log(LIGHT)$	$\log(HEAVY)$
$COVERAGE_{t-1}$	-0.123*	-0.108	-0.456***	-0.137*	0.00455
	(0.0666)	(0.0719)	(0.154)	(0.0681)	(0.120)
R^2	0.530	0.459	0.295	0.500	0.210
1st Stage F-statistic	23.84	23.84	23.84	23.84	23.84
Motorway sector	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Observations	700	700	700	700	700

impact of new government regulations (e.g., the introduction of a penalty-point system for driving licensees in 2003 and the strengthening of penalties for road traffic offences in 2007).

Moreover, our estimates might still be biased due to omitted variables and reverse causality. To address problems stemming from these additional endogeneity issues, we utilized an instrumental variable strategy by exploiting the membership of some motorway sectors in the Autostrade per l'Italia group as an instrument for Safety Tutor. 2SLS results show no evidence of a causal effect of Safety Tutor on preventing highway accidents in any of the categories analysed. The key insight is that our IV estimator is informative about the average effect of the subgroup of the "complier" motorway sectors. Moreover, we are aware that a limitation of our analysis involves the plausible presence of spillover effects that could attenuate our findings.

There are many possible explanations for this lack of effect: first, Safety Tutor activation was progressively limited to a few hours per day and alternated between various camera sites installed along the same motorway sector (due to the large amount of data to be processed); thus, after an initial deterrent effect, a gradual reduction in drivers' compliance with speed limits might have taken place a few months following the installation of each camera site, as explained by Montella et al. (2015b). Second, the 12-year legal process for patent rights might have encouraged the concessionaires to limit investments in new Safety Tutor installations or to reduce operational activities. Third, the average speed enforcement has a partial deterrent effect on peak speed, as drivers might speed in some sectors and then slow down in others, increasing the crash risk. This explanation can be supported by the absence of significant correlation between Safety Tutor coverage and heavy vehicle accidents even in the OLS estimates, as trucks are hardly able to exceed highway speed limits. Finally, traffic and congestion (on which Safety Tutor has no impact) can be a more important cause of accidents than speed.

As our results show no evidence of a significant causal effect of Safety Tutor in preventing highway accidents, we suggest a better implementation of average speed enforcement systems by increasing both the number of hours of activation and the utilization of entry and exit camera sites as fixed speed cameras. Moreover, the allocation of resources for accident prevention programmes on high-speed roads should not focus only on enforcing speed limits, but they might also target improving the paving and increasing the capacity of highly congested motorway sectors. Since accident prevention is a major goal of transport institutions and road agencies (as foreseen by the "Zero Road Deaths and Serious Injuries" programme), this paper ultimately seeks to show how the utilization of robust econometric methods (which control for confounding factors and take into account endogeneity issues) can help highway concessionaires in the analysis of their increasing amount of available data to better evaluate accident prevention policies.

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Appendix

Table A: Variable definitions and sources

Variable	Variable definition	Source
ACCIDENTS	Annual vehicle accidents occurred within the motorway property that caused injuries or death to people	AISCAT[1]
INJURED	Annual people injured by vehicle accidents	AISCAT[1]
FATALITIES	Annual deaths occurring within 30 days of the vehicle accident	AISCAT[1]
LIGHT	Annual accidents involving only motorcycles and two-axle vehicles with the front axle below 1.30 metres from ground	AISCAT[1]
HEAVY	Annual accidents involving only two-axle vehicles with the front axle above 1.30 metres from ground and vehicles with three or more axles	AISCAT[1]
DAILY_TRAFFIC	Annual average daily number of vehicles of all types transited along a motorway sector, regardless of the kilometres travelled	AISCAT[1]
DAILY_TRAFFIC_LIGHT	Annual average daily number of light vehicles of all types transited along a motorway sector, regardless of the kilometres travelled	AISCAT[1]
DAILY_TRAFFIC_HEAVY	Annual average daily number of heavy vehicles of all types transited along a motorway sector, regardless of the kilometres travelled	AISCAT[1]
HIGHWAY_LENGTH	Annual length (in kilometres) of each motorway sector	AISCAT[1]
TUTOR_LENGTH	Annual length (in kilometres) of each motorway sector covered by Safety Tutor sites	ASPI[2]
COVERAGE	Annual ratio between *TUTOR_LENGTH* and *HIGHWAY_LENGTH*	Authors' calculation
ALCOHOL_PC	Annual per capita ethanol consumption (in litres) for all beverages	GHO[3]
VEHICLES_AGE	Annual average age of circulating vehicle fleet (in years)	ISPRA[4]
TECHNOLOGY	Dummy variable equalling one in 2005-2015	Authors' calculation
ASPI_GROUP	Dummy variable equalling one for those motorway sectors managed by Autostrade per l'Italia and its controlled concessionaires	Authors' calculation
INSTRUMENT	Dummy variable equalling the product between *TECHNOLOGY* and *ASPI_GROUP*	Authors' calculation

Notes: [1] Associazione Italiana Società Concessionarie Autostrade e Trafori, [2] Autostrade per l'Italia, [3] Global Health Observatory, [4] Istituto superiore per la protezione e la ricerca ambientale.

Table B: Progressive deployment of Safety Tutor sites, 2005-2011. For each motorway sector, *Safety Tutor site* shows the exact entry and exit kilometre where cameras are installed, corresponding to the maximum *TUTOR_LENGTH* (between the two carriageways) reached in 2011. *TUTOR_LENGTH* shows the number of kilometres covered by Safety Tutor sites as of 31 December of each year

Motorway sector	Safety Tutor site	*TUTOR_LENGTH*						
		2005	2006	2007	2008	2009	2010	2011
A1 Milano-Bologna	San Zenone al Lambro 12.1 - Bivio A1/A14 186.9	0.0	0.0	0.0	99.3	174.8	174.8	174.8
A1 Firenze-Roma	Orte 489.9 - Roma 534.7	0.0	0.0	1.7	21.8	44.8	44.8	44.8
A1 Roma-Napoli	Roma 534.7 - Caserta Nord 736.7	0.0	0.0	202.0	202.0	202.0	202.0	202.0
A1 Collegamento Firenze-Roma-Napoli	San Cesareo 3.8 - Monteporzio Catone 11.0	0.0	0.0	0.0	0.0	0.0	7.2	7.2
A3 Napoli-Salerno	Scafati 25.0 - Angri 29.8	0.0	0.0	0.0	0.0	0.0	4.8	4.8
A3 Napoli-Salerno	Cava Dei Tirreni 42.8 - Salerno 51.7	0.0	0.0	0.0	0.0	0.0	8.9	8.9
A4 Milano-Brescia	Agrate 146.9 - Brescia Ovest 217.0	70.1	70.1	70.1	70.1	70.1	70.1	70.1
A4 Brescia-Padova	Brescia Est 225.9 - Somma Campagna 273.5	0.0	0.0	0.0	37.2	37.2	37.2	47.6
A4 Venezia-Trieste	Venezia Est 20.8 - Bivio A4/A23 92.0	0.0	0.0	0.0	0.0	0.0	0.0	71.2
A4 Venezia-Trieste	Palmanova 97.8 - Redipuglia 108.7	0.0	0.0	0.0	0.0	0.0	0.0	10.9
A6 Torino-Savona	Carmagnola 14.4 - Marene 33.4	0.0	0.0	0.0	0.0	0.0	19.0	19.0
A6 Torino-Savona	Millesimo 91.1 - Ceva 85.0	0.0	0.0	0.0	0.0	0.0	6.1	6.1
A6 Torino-Savona	Altare 118.5 - Bivio A6/A10 122.6	0.0	0.0	0.0	0.0	0.0	4.1	4.1
A7 Genova-Serravalle	Isola del Cantone 99.2 - Genova Bolzaneto 125.1	0.0	0.0	0.0	12.3	12.3	25.9	25.9
A8 Milano-Varese/A9 Lainate-Chiasso	Origgio Ovest 12.2 - Gallarate 29.0	0.0	0.0	0.0	0.0	16.8	16.8	16.8
A13 Bologna-Padova	Arcoveggio 1.4 - Padova Zona Ind. 114.2	7.9	7.9	7.9	94.2	112.8	112.8	112.8
A14 Bologna-Ancona	Biv.A14/Rac. Casalecchio 9.1 - Rimini Nord 118.4	29.2	29.6	29.6	95.1	109.3	109.3	109.3
A14 Ancona-Pescara	Giulianova 327.0 - Bivio A14/A25 374.9	0.0	0.0	0.0	39.5	39.5	47.9	47.9
A14 Pescara-Canosa	Bivio A14/A25 374.9 - Bivio A14/A16 600.0	0.0	201.8	201.8	205.3	205.3	205.3	225.1
A14 Canosa-Bari-Taranto	Bivio A14/A16 605.5 - Bari Sud 682.0	0.0	0.0	0.0	0.0	0.0	73.0	76.5
A23 Palmanova-Udine	Bivio A23/A4 3.2 - Udine Sud 16.6	0.0	0.0	0.0	0.0	0.0	0.0	13.4
A23 Udine-Tarvisio	Udine Nord 25.2 - Ugovizza 104.5	0.0	0.0	0.0	0.0	0.0	66.0	79.3
A24 Roma-Torano	Tivoli 14.5 - Carsoli 51.5	0.0	0.0	37.0	37.0	37.0	37.0	37.0
A24 Torano-Teramo	Valle del Salto 74.6 - L'Aquila Ovest 108.0	0.0	0.0	33.4	33.4	33.4	33.4	33.4
A25 Torano-Pescara	Avezzano 87.1 - Sulmona 137.9	0.0	0.0	50.8	50.8	50.8	50.8	50.8
A26 Voltri-Alessandria	Bivio A26/A10 1.7 - Bivio A26/Predosa-Bettole 44.5	0.0	30.0	30.0	30.0	42.8	42.8	42.8
A28 Portogruaro-Conegliano	Villotta 6.6 - Azzano-Decimo 15.2	0.0	0.0	0.0	0.0	0.0	0.0	8.6
A30 Caserta-Nola-Salerno	Bivio A30/A1 1.3 - Castel San Giorgio 42.8	0.0	0.0	0.0	0.0	41.5	41.5	41.5
A56 Tang.le di Napoli	Astroni 4.3 - Fuorigrotta 9.9	0.0	0.0	0.0	0.0	5.6	5.6	5.6
A56 Tang.le di Napoli	Vomero 11.4 - Camaldoli 13.2	0.0	0.0	0.0	0.0	1.8	1.8	1.8
A56 Tang.le di Napoli	Arenella 15.4 - Capodimonte 17.4	0.0	0.0	0.0	0.0	2.0	2.0	2.0
Total		107.2	339.4	664.3	1 028.0	1 239.8	1 450.9	1 602.0

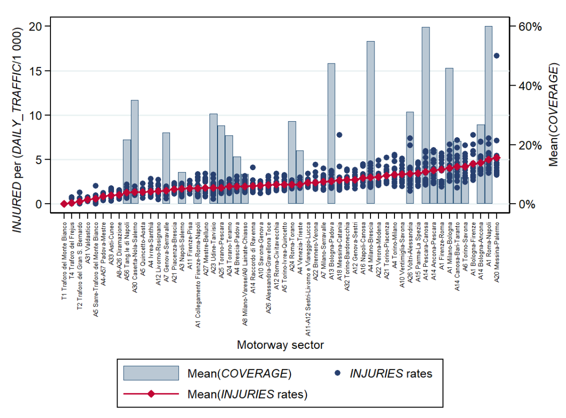
Notes: The other 33 motorway sectors free of Safety Tutor sites are T1 Traforo del Monte Bianco, T2 Traforo del Gran S. Bernardo, T4 Traforo del Frejus, A5 Sarre-Traforo del Monte Bianco, A32 Torino-Bardonecchia, A33 Asti-Cuneo, A5 Quincetto-Aosta, A5 Torino-Ivrea-Quincetto, A4 Ivrea-Santhià, A26 Alessandria-Gravellona Toce, A8-A26 Diramazione, A7 Milano-Serravalle, A22 Brennero-Verona, A22 Verona-Modena, A31 Valdastico, A15 Parma-La Spezia, A14 Raccordo di Ravenna, A4 Torino-Milano, A4 Padova-Mestre, A27 Mestre-Belluno, A21 Torino-Piacenza, A21 Piacenza-Brescia, A10 Ventimiglia-Savona, A10 Savona-Genova, A12 Genova-Sestri, A12 Livorno-Rosignano, A11-A12 Sestri-Livorno e Viareggio-Lucca, A1 Bologna-Firenze, A11 Firenze-Pisa, A12 Roma-Civitavecchia, A16 Napoli-Canosa, A18 Messina-Catania, A20 Messina-Palermo.

Table C: 2001 and 2015 *HIGHWAY_LENGTH* per motorway sector.

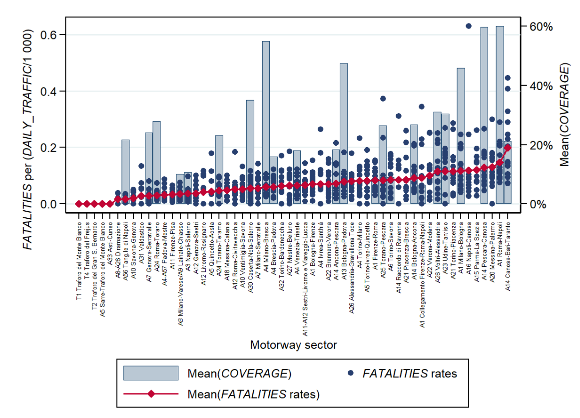
Motorway sector	*HIGHWAY_LENGTH*		Motorway sector	*HIGHWAY_LENGTH*	
	2001	2015		2001	2015
T1 Traforo del Monte Bianco[1]	5.8	5.8	A12 Livorno-Rosignano[17]	36.6	40.0
T2 Traforo del Gran S. Bernardo[2]	12.8	12.8	A12 Roma-Civitavecchia[4]	65.4	65.4
T4 Traforo del Frejus[3]	6.8	6.8	A13 Bologna-Padova[4]	127.3	127.3
A1 Milano-Bologna[4]	192.1	192.1	A14 Bologna-Ancona[4]	236.0	236.0
A1 Bologna-Firenze[4]	91.1	91.1	A14 Raccordo di Ravenna[4]	29.3	29.3
A1 Firenze-Roma[4]	273.0	273.0	A14 Ancona-Pescara[4]	133.8	133.8
A1 Roma-Napoli[4]	202.0	202.0	A14 Pescara-Canosa[4]	239.3	239.3
A1 Collegamento Firenze-Roma-Napoli[4]	45.3	45.3	A14 Canosa-Bari-Taranto[4]	143.0	143.0
A3 Napoli-Salerno[5]	51.6	51.6	A15 Parma-La Spezia[18]	101.0	101.0
A4 Torino-Milano[6]	127.0	127.0	A16 Napoli-Canosa[4]	172.3	172.3
A4 Ivrea-Santhià[7]	23.6	23.6	A18 Messina-Catania[19]	76.8	76.8
A4 Milano-Brescia[4]	93.5	93.5	A20 Messina-Palermo[19]	140.6	181.8
A4 Brescia-Padova[8]	146.1	146.1	A21 Torino-Piacenza[6]	164.9	164.9
A4-A57 Padova-Mestre[9,a]	23.3	74.1	A21 Piacenza-Brescia[20]	88.6	88.6
A4 Venezia-Trieste[10,b]	180.3	210.2	A22 Brennero-Verona[21]	224.0	224.0
A5 Torino-Ivrea-Quincetto[7]	51.2	51.2	A22 Verona-Modena[21]	90.0	90.0
A5 Quincetto-Aosta[11]	59.5	59.5	A23 Udine-Tarvisio[4]	101.2	101.2
A5 Sarre-Traforo del Monte Bianco[12]	27.0	32.4	A24 Roma-Torano[22]	79.5	79.5
A6 Torino-Savona[13]	130.9	130.9	A24 Torano-Teramo[22]	87.0	87.0
A7 Genova-Serravalle[4]	50.0	50.0	A25 Torano-Pescara[22]	114.9	114.9
A7 Milano-Serravalle[14]	86.3	86.3	A26 Voltri-Alessandria[4]	83.7	83.7
A8 Milano-Varese/A9 Lainate-Chiasso[4]	77.7	77.7	A26 Alessandria-Gravellona Toce[4]	161.2	161.2
A8-A26 Diramazione[4]	24.0	24.0	A27 Mestre-Belluno[4]	82.2	82.2
A10 Ventimiglia-Savona[15]	113.3	113.3	A30 Caserta-Nola-Salerno[4]	55.3	55.3
A10 Savona-Genova[4]	45.5	45.5	A31 Valdastico[8]	36.4	89.5
A11 Firenze-Pisa[4]	81.7	81.7	A32 Torino-Bardonecchia[3]	72.4	75.7
A11-A12 Sestri-Livorno e Viareggio-Lucca[16]	154.9	154.9	A33 Asti-Cuneo[23,c]	39.4	55.7
A12 Genova-Sestri[4]	48.7	48.7	A56 Tang.le di Napoli[24]	20.2	20.2

Notes: For each motorway sector, the related highway concession company is [1] Società Italiana per il Traforo del M. Bianco S.p.A., [2] Società Italiana per il Traforo del G.S. Bernardo S.p.A., [3] Società Italiana per il Traforo del Frejus S.p.A., [4] Autostrade per l'Italia S.p.A., [5] Autostrade Meridionali S.p.A., [6] Società Autostrada Torino-Alessandria-Piacenza S.p.A., [7] Autostrada Torino-Ivrea-Valle d'Aosta S.p.A., [8] Autostrada Brescia-Verona-Vicenza-Padova S.p.A., [9] Concessioni Autostradali Venete - C.A.V. S.p.A., [10] Autovie Venete S.p.A., [11] Società Autostrade Valdostane S.p.A., [12] Raccordo Autostradale Valle d'Aosta S.p.A., [13] Autostrada Torino-Savona S.p.A., [14] Milano Serravalle-Milano Tangenziali S.p.A., [15] Autostrada dei Fiori S.p.A., [16] Società Autostrada Ligure Toscana S.p.A., [17] Società Autostrada Tirrenica S.p.A., [18] Autocamionale della Cisa S.p.A., [19] Consorzio per le Autrostrade Siciliane, [20] Autostrade Centro Padane S.p.A., [21] Autostrada del Brennero S.p.A., [22] Strada dei Parchi S.p.A., [23] Autostrada Asti-Cuneo S.p.A., [24] Tangenziale di Napoli S.p.A. [a] Until 2009 the Padova-Mestre sector was managed by Società Autostrade di Venezia e Padova S.p.A., [b] It includes also A23 Palmanova-Udine, A28 Portogruaro-Conegliano, A34 Villesse-Gorizia, and a sector of A57 Tangenziale di Mestre, [c] The Asti-Cuneo sector started operations in 2008.

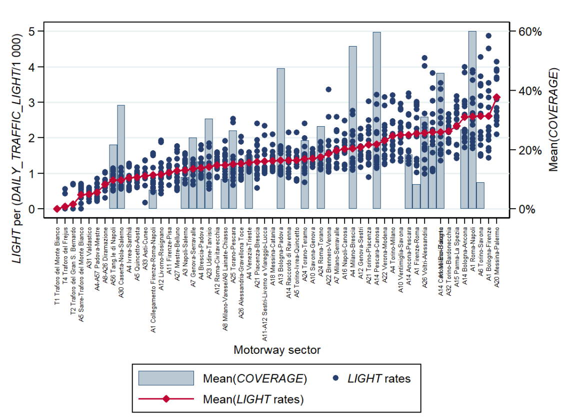
Figure A: Heterogeneity of accident category rates across motorway sectors



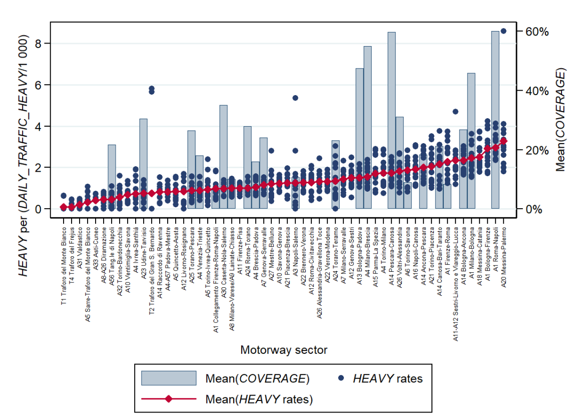
(a) *INJURED* rates by motorway sector



(b) *FATALITIES* rates by motorway sector

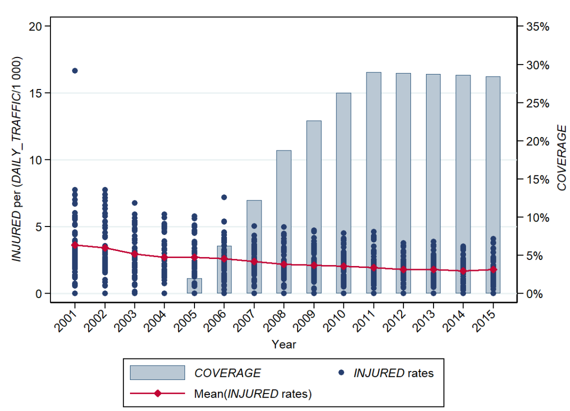


(c) *LIGHT* rates by motorway sector

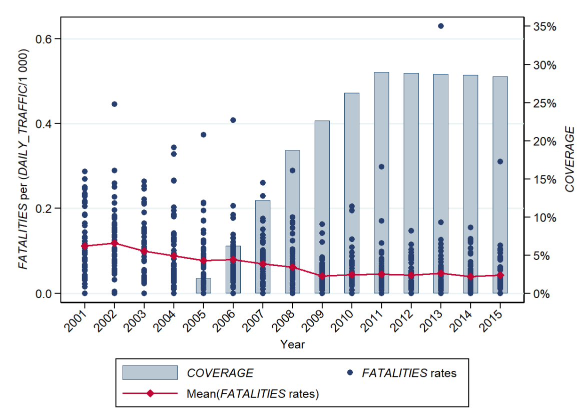


(d) *HEAVY* rates by motorway sector

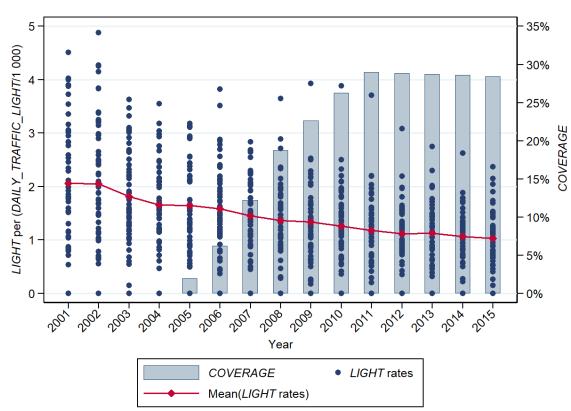
Figure B: Heterogeneity of accident category rates across years, 2001-2015



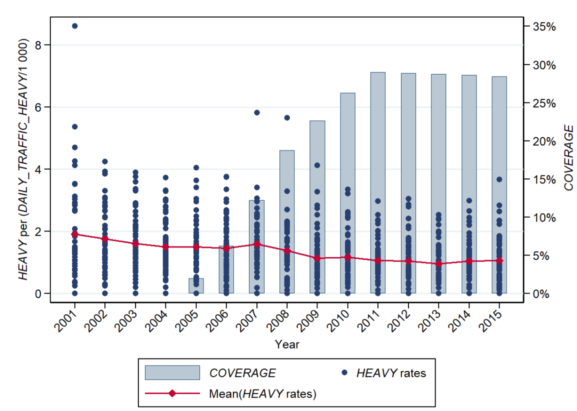
(a) *INJURED* rates by year



(b) *FATALITIES* rates by year



(c) *LIGHT* rates by year



(d) *HEAVY* rates by year