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On interurban road pricing schemes and the impacts of traffic diversion on road safety in Germany: Empirical findings and implications

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Recently, traffic diversion effects induced by tolling have increasingly been attracting attention, since interurban road charging schemes are becoming more widespread in Europe. However, less attention has been paid to unintended spillover effects concerning negative road safety outcomes, caused by traffic shifts to non-tolled adjacent secondary roads of inferior quality. This study introduces to the specifics of existing road pricing schemes in Europe, clarifies the characteristics of the German toll system and explores the relationship between toll implementation and road safety outcomes using regional German panel data for the period 2000-2010. To this end, we test different specifications using accident data, while controlling for transport-related and socio-economic covariates. We find that the implementation of the heavy goods vehicle toll in 2005 has a negative impact on accident rates with damage to persons during our sample period. This finding is a valuable insight for policy makers, since the existence of a relationship between tolls, traffic diversion and road safety has important policy implications regarding the determination of optimal welfare-enhancing tolls.

Keywords: h*eavy goods vehicle toll, road pricing, road safety, traffic diversion.*

1. Introduction

In Europe, road infrastructure charging has become a key issue of transport policy since numerous charging schemes were implemented both in urban and interurban environments over the last few decades. Tolls were introduced mainly to combat congestion in metropolitan areas or to finance new developments and the expansion of interurban road networks. Recent studies confirm the substantial positive impact of urban congestion charges on reducing traffic volumes (see, for example, Santos, 2005; Olszewski, 2007; Eliasson, 2009; De Palma and Lindsey, 2011), but perceptions still differ regarding the welfare outcomes (Prud´homme and Boccajero, 2005; TfL, 2007). While urban road pricing solutions are rarely implemented, charging for interurban road infrastructure has a long tradition in European countries.

Different toll systems and charging models have emerged over recent years and a considerable degree of heterogeneity between existing schemes has evolved. In practice, the main focus of price setting is on the recovery of construction and maintenance costs and on the internalisation of congestion-related externalities. However, the basic idea of road pricing developed in the fundamental works by Pigou (1920), Knight (1924), Walters (1961) and Vickrey (1963) has been extended in recent times. For example, Newberry (1990), Verhoef (1994), Verhoef et al. (1995), Maddison et al. (1996) and Rothengatter (2000) propose to internalise diverse external cost components, such as regional and global environmental effects, noise and accident costs. This

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development is promoted by the enhanced public perception of health and environmental issues, as well as the progress made in road pricing technology that enables the practical implementation of more complex tariff structures (Johansson-Stenman and Sterner, 1998; De Palma and Lindsey, 2011). Over the last ten years, the number of road pricing schemes containing environmental price components has increased substantially. This includes, for instance, the urban road pricing scheme in Milan (Rotaris et al., 2010) or the interurban toll schemes for heavy goods vehicles in Germany (Wieland, 2005) and Austria (ASFINAG, 2012).

By contrast, the effects of interurban tolls on road safety remain largely neglected. Nevertheless, this aspect is of considerable importance, particularly given that several theoretical (Braid, 1996; Verhoef et al., 1996; De Palma and Lindsey, 2000) and empirical studies (ASFINAG, 2004; Deutscher Bundestag, 2005; Rothengatter, 2005) point to the traffic diversion effects induced by the implementation of tolls. Due to the fact that interurban charging schemes are often geographically limited to motorway networks, a traffic shift to non-tolled adjacent secondary roads of (potentially) inferior quality can be expected. As a result of this so-called 'rat running' or 'rerouting' effect, the number of accidents might increase on certain alternative routes (Verhoef et al., 1996; Albalate and Bel, 2012).

To date, there have been very few studies on interurban road tolls, traffic diversion effects and road safety outcomes. The few empirical studies that there are, identify a significant relationship between tolling and the number of road accidents (Albalate, 2011; Albalate and Bel, 2012; Swan and Belzer, 2013). Owing to the high degree of heterogeneity between countries with respect to road infrastructures and interurban toll models, further investigation is needed to clarify the safety effects of road tolls.

The major research issue addressed in this paper is to determine the impact of road charges on the number of severe accidents causing injuries and fatalities. In Germany, surveys are still limited to investigations of traffic diversion effects caused by heavy goods vehicle tolling (Deutscher Bundestag, 2005, 2009 and 2013). Our findings show that interurban tolls not only cause traffic diversion but also have a negative impact on road safety in Germany. This result indicates that the current price setting process produces socially inefficient spillover effects, an outcome that is consistent with the general findings in Albalate (2011) regarding Spain. However, we observe large differences between both toll systems, as the German road pricing scheme applies for all motorways, is limited to heavy goods vehicles (above 12t) and is based on a homogenous tariff structure. This paper attempts to improve the empirical basis of this field of research by taking into consideration the safety outcomes of distance-related large-scale toll systems that are limited to heavy goods vehicles. Considering the different charging schemes existing in Europe, our findings may constitute a valuable insight for policy makers in Germany and countries with analogous toll systems. Furthermore, as the current development in Europe shows, the number of toll schemes is even likely to increase in the future.

This study proceeds as follows. In Section 2, we provide a brief overview of traffic diversion effects and present some background information on the German heavy goods vehicle toll (HGV toll). Section 3 describes the data and the methodology used in this study to quantify the impact of tolling on road safety. Section 4 discusses the estimation results as well as the limitations of the study. In Section 5, we consider the implications for policy makers. Finally, Section 6 concludes.

2. Background

2.1 *Traffic diversion effects induced by interurban tolls*

Economic theory states that an inefficient pricing of road networks can create substantial traffic diversion effects. Levy-Lambert (1968) and Marchand (1968) were the first to study the case of a two-link network, consisting of one tolled and one tollfree road. Their findings indicate that the implementation of one-route first-best tolling, only considering the social costs on the tolled road, results in a shift of traffic and a subsequent loss of welfare, due to overutilisation of the non-tolled road. In this context, Verhoef et al. (1996) recommend the application of a second-best toll that is lower than the social marginal external costs created on the charged road. The actual price level depends on factors such as the elasticity of demand and the quality of the adjacent tollfree road. In conclusion, a second-best efficient pricing of individual (e.g. congested) links may be beneficial, although Verhoef and Small (2004) demonstrate that charging for the whole road network produces more efficient welfare outcomes.

At present, numerous European countries charge for the use of interurban roads. However, the structure of these road pricing systems varies according to the type of scheme (distance-related or time-based), their scope (motorways, expressways or local roads), the degrees of price differentiation (e.g., vehicle weight, time of day or environmental characteristics) and the technology used (manual or electronic charging). As a result, we observe various toll avoidance strategies which depend on the particular charging system (Martino et al., 2008). Firstly, the likelihood of modal shift increases, particularly when the road toll causes significantly higher costs of road infrastructure use in comparison to other transport modes. Secondly, an optimisation of transport procedures can be expected, such as increasing load factors and reduced empty runs. Thirdly, the composition of the vehicle fleet may change, in relation to the determined elements of tariff differentiation. Finally, different forms of traffic diversion can be identified. Depending on the scope of the road pricing scheme and the road quality, rat running occurs in form of an intensified use of alternative cost saving routes, for instance, short- and long haul national routes, as well as international routes (Kummer and Nagl, 2005).

Rat running has generated a great deal of attention, particularly in countries using distance-related tolls, for example in Austria (ASFINAG, 2004), Germany (Deutscher Bundestag, 2005), the Czech Republic (Liechti and Renshaw, 2007) and Spain (Albalate, 2011). From an economic perspective, these systems offer advantages over time-based schemes, because external effects can (theoretically) be charged according to the polluter-pays principle. Nevertheless, practical experience shows that charges are based essentially on cost recovery and therefore fail to meet the criterion of second-best efficiency.

As a consequence, traffic will divert to non-tolled roads if there is cost-saving potential from the road user perspective and will lead to unintended spillovers such as noise, additional emissions, lower productivity or revenue losses (Kummer and Nagl, 2005). Moreover, rerouting predominantly shifts traffic to roads of lower quality, which might cause additional congestion or increasing safety costs. Albalate and Bel (2012) provide some empirical evidence of the existence of the latter effect.[2] Their analysis suggests that road safety is a relevant factor that should be taken into consideration.

2.2 *The German HGV toll*

In Germany, public budgets have traditionally been used to finance road infrastructure investments. Nevertheless, Germany joined the Eurovignette system in 1995 and introduced, for the first time ever, direct charges for the use of interurban roads.[3] The main intention of this policy was to improve the harmonisation of conditions for competition in Europe (Wieland, 2005). Until August 2003, all heavy goods vehicles with a gross vehicle weight (GVW) above 12t using German motorways (about 12.000 kilometres) were subject to time-based tolls. Due to the time-based character and the broad geographical scale covered by this type of road toll, traffic diversion effects were not expected and accordingly have not been reported during the period in which the Eurovignette scheme was operated.

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[2] Albalate and Bel (2012) use a panel containing data from six European countries (Austria, France, Greece, Italy, Portugal and Spain) for the period 1991-2003.

[3] The Eurovignette system was implemented in cooperation with Denmark, Belgium, Luxemburg and the Netherlands. Sweden joined in 1998.

In order to prevent financial bottlenecks in infrastructure funding, the German government commissioned a group of experts (Pällmann, 2000) to develop proposals for future financing of transport infrastructure. The final decision to introduce an electronic distance-related charging scheme was based mainly on the recommendations made by this Commission. With the implementation of the new charging scheme ('LKW-Maut'), the following objectives are to be achieved: application of the polluter-pays principle in allocating costs; improvement of the competitive conditions between road, rail and waterways; improvement of environmental protection and revenue creation (BMVBS, 2012a). Due to technical and organisational problems, the operation of the toll scheme for HGV with a GVW above 12t started after a delay of sixteen months, causing a substantial revenue loss. Finally, the GNSS/GSM-based HGV toll was launched in January 2005 and has been running without major disruptions since then. The calculation base for the rates is derived from infrastructure costing, including the costs of capital and operating expenses (Doll and Schaffer, 2007). Basically, the toll tariff is distance-related and homogenous for all roads. However, with regard to the computation of infrastructure costs, the allocation follows the axle configuration and the emission standard of the vehicle as described in Table 1.

Table 1. HGV toll tariff structure in 2012 (in Euro per kilometre)

	Vehicle categories			
	A	B	C	D
Axles	[S5, EEV class 1, S6]	[S4, S3 PMK with 2, 3 or 4]	[S3 without PMK, S2 with PMK 1, 2, 3 or 4]	[S2 without PMK, S1 and vehicles not covered by any S]
Up to 3	0.141	0.169	0.190	0.274
4 and more	0.155	0.183	0.204	0.288

Notes: S (Emission class), EEV (Enhanced Environmentally Friendly Vehicle), PMK (Particle reduction class).
Source: Toll Collect (2012).

The implementation of the HGV toll has impacts in several areas. Between 2005 and 2012, annual revenues increased constantly from € 2.90 billion to € 4.36 billion. This represents a major growth compared with the toll revenues of less than € 500 million p.a. generated by the Eurovignette system. In addition, the HGV tolling scheme contributes to transport infrastructure funding through the earmarking of revenues (BMVBS, 2012a). Moreover, a trend towards cleaner vehicles could be observed. This might be related to the emission-based differentiation of tariffs (DIFFERENT, 2007; Doll and Schaffer, 2007). But the internalisation of external costs is not the main objective of the HGV charging scheme. For this reason and due to the distance-related tolling that is limited to the motorway network, traffic diversion effects could be expected. This refers both to economic theory and practical experience, for example, in Austria where hauliers avoided tolled motorways after the implementation of a distance-related HGV charge (vehicles with a GVW > 3.5t). In 2004, a total of 2.8% of Austrian motorway traffic diverted to the subsidiary road network, although traffic increased up to 100% on individual links (ASFINAG, 2004). In 2005, after the introduction of the HGV toll in Germany, several federal states and communities noticed a substantial traffic growth. On non-tolled road sections, dramatic increases in daily traffic could be observed, with growth rates of even exceeding 100% (Wieland, 2005). The first official investigation published in December 2005 concluded that average daily traffic increased by at least 50 HGVs on 26.7%[4] of the federal road network ('Bundesstraßen'). On 5.1% of federal roads, the daily traffic grew by at least 150 HGVs (Deutscher Bundestag, 2005). In the event of large-scale traffic diversion, federal states and communities have the correction option of

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[4] These are 11,100 kilometres out of a 41,200 kilometre total length of the federal road network.

expanding the HGV toll to affected federal roads and by using regulatory interventions, such as traffic restrictions (by time, vehicle class, etc.) and speed limits.[5]

As we have seen, there are several objective indications that traffic diversion could potentially affect road safety outcomes in Germany. Firstly, HGV tolling shifts traffic to roads with a generally lower quality (the level of traffic diversion depends on the specific price elasticity of demand), although the federal road network is well developed. On these subsidiary roads, for instance, missing central barriers, opposing traffic or crossroads might have a negative impact on road safety. It can be seen from Figure 1 that during our sample period the probability of severe accidents on motorways is indeed smaller compared to other road categories in Germany. Secondly, pricing ignores most of the social costs generated on the total road network, which also includes the additional accident costs caused by rat running.

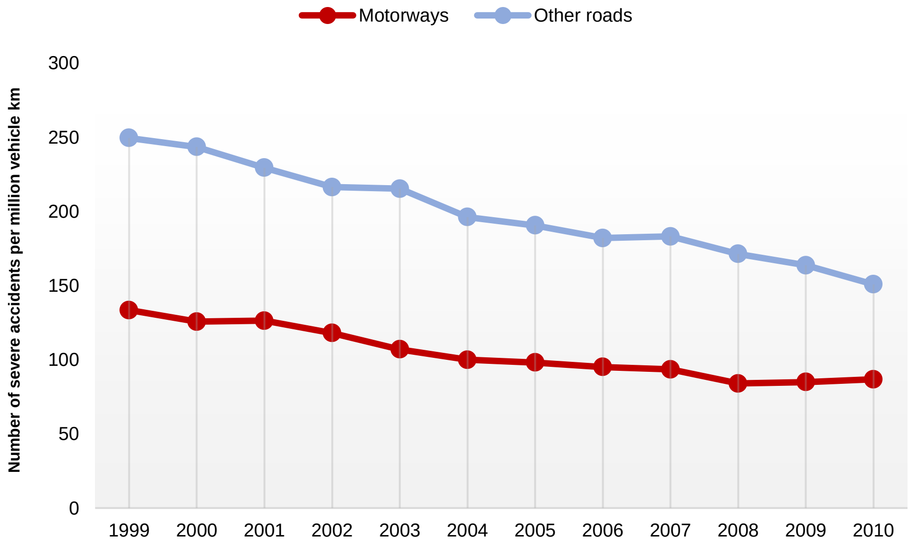

Figure 1. Number of severe accidents per million vehicle kilometres in Germany 1999-2010

3. Data and Methodology

In order to test the hypothesis, we use aggregate data at NUTS-1 level ('Bundesländer') to compute the impact of tolling on road safety for German regions during the period between 2000 and 2010. The results provide valuable insights into spillover effects that are produced unintentionally by tolls levied on the interurban road infrastructure.

The data used in this study was compiled from various sources. Information on several transport and socio-economic variables, including accidents rates, road network data, motorisation degrees, GDP growth and population data are published regularly by the German Federal Statistical Office (Statistisches Bundesamt). The German Federal Highway Research Institute (Bundesanstalt für Straßenwesen) provides data on the percentage share of heavy utilities on different road categories. In addition, information on alcohol and drug abuse, speeding and driving license offences is provided by the German Federal Motor Transport Authority (Kraftfahrtbundesamt). This data is not frequently published, but available upon request. The unbalanced panel covers 16 regions over a period of 11 years.[6]

We use two dependent variables in our estimations. These are *Accident Rate* (all roads), computed as the total number of accidents with damages to persons (including all kinds of injuries and road

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[5] In compliance with § 1 BFStrMG (Bundesfernstraßenmautgesetz) and § 45 StVO (Straßenverkehrsordnung).
[6] Five observations are missing, due to data limitations.

fatalities) on all roads in region *i* during year *t*, and *Accident Rate* (non-tolled roads), computed as the total number of accidents with damage to persons on non-tolled roads in region *i* during year *t*. To ensure comparability between regions, both rates are normalised per 100,000 inhabitants.

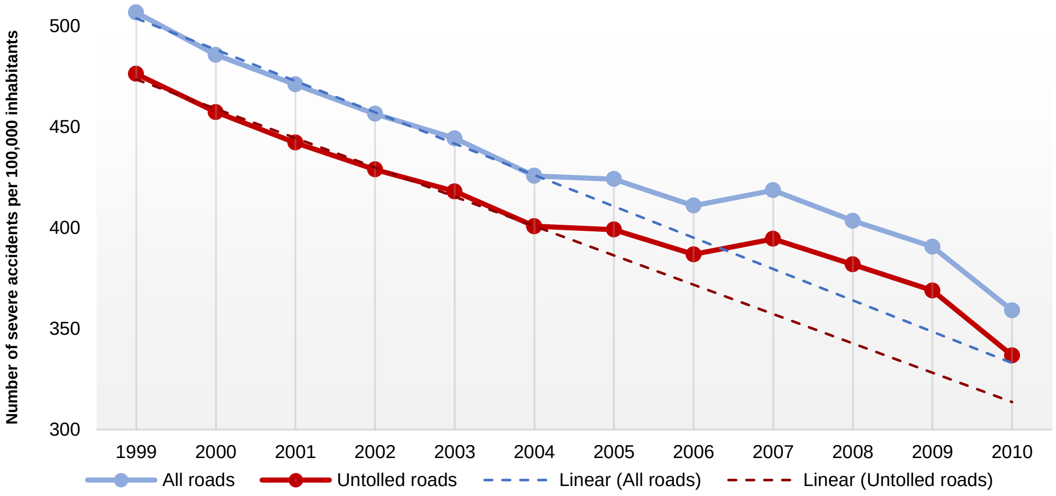

Figure 2. Mean of the number of accidents with damage to persons (all roads and non-tolled roads) per 100,000 inhabitants between 1999 and 2010 in Germany

As can be seen in Figure 2 the number of accidents with damage to persons exhibits a pronounced negative time trend between 1999 and 2010. The dashed lines additionally display linear trend explorations based on the accident numbers during the period 1999 to 2004 for both key variables. As the figure shows, the absolute number of accidents is constantly above this trend line, which implies at least a relative increase in the number of severe accidents during the period 2005 to 2010 that may be (partially) attributed to the introduction of the HGV toll. However, the toll effect is not strong enough to reverse the trend in the number of severe accidents.

In the case that toll implementation causes traffic diversion, we would most likely expect increasing accident rates particularly on non-tolled roads. Instead, we observe that both key figures are closely related. This can be attributed to the fact that the German road network consists primarily of untolled roads (about 88%). In addition, if the toll hypothesis is true, the anticipated increase in the number of accidents on untolled roads should be larger than the anticipated decrease in the number of accidents on tolled roads. Therefore, rerouting may have a major influence on the accident rates on untolled roads. However, further analysis is needed in order to identify whether rerouting causes an increase in the total accident level (and consequently increasing external accident costs) and not merely an 'identical shift of accidents' between different road types. This would imply that the number of accidents on tolled roads could decrease due to traffic diversion while it increases to the same extent on non-tolled roads). For this reason, we also test a specification including an accident variable for all road types as a dependent variable.

To evaluate the effects stemming from HGV tolls in Germany, we include a dummy variable *Toll*, indicating the implementation of the road charging system in 2005. If only the level of accidents is affected and not the rate of change, there should be a persistent one-off increase in the accident rate when the toll comes into effect. This is covered by our toll dummy variable, which is one from 2005 on and zero otherwise.[7] It should be noted that this dummy variable takes the same

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[7] In the first difference model, it is consequently one in 2005 and zero otherwise.

value for all individuals, since the implementation took place simultaneously in all German regions.

Besides the toll dummy, several transport-related variables are considered in the regression, including the proportion of *Motorway* kilometres over the total road network. As mentioned by Albalate (2012), extending the motorway network might foster positive safety outcomes regarding the high safety standards applied to this road category.

Motorisation is measured as the number of passenger cars per capita. A higher degree of vehicle ownership is associated with higher traffic volumes and therefore, more accidents are expected. But increasing motorisation might also produce higher levels of congestion, particularly in urban areas, leading to decreasing average speeds and a potentially reduced risk of severe accidents (Albalate and Bel, 2011). We also include the percentage share of *HGV Traffic* on motorways and primary roads. The accident involvement of heavy utilities might increase the severity of accidents, by reason of their significantly higher vehicle weight and as a consequence of higher speeds on interurban roads (Bédard et al., 2002; European Transport Safety Council, 2005).

Table 2. Descriptive statistics

Variable	Definition	Min.	Max.	Mean	Median	Std. Dev.
Transport variables						
Accident Rate (all roads)	Number of accidents with damage to persons per 100,000 inhabitants	302.86	598.10	432.99	430.70	57.18
Accident Rate (non-tolled roads)	Number of accidents with damage to persons per 100,000 inhabitants	277.63	579.33	407.58	402.75	55.82
Toll	Dummy Variable	0.00	1.00	-	-	-
Motorways	Proportion of motorway km over the total road network (in %)	2.39	64.66	12.41	5.47	15.91
Motorisation	Number of passenger cars per 1,000 inhabitants	316.10	572.11	474.90	490.16	57.91
HGV Traffic.mpr	Average share of heavy vehicles on motorways and primary roads	5.85	14.46	10.89	11.17	1.88
HGV Traffic.pr	Average share of heavy vehicles on primary roads	3.25	13.00	8.54	8.66	2.08
Socio-economic variables						
Age Structure	Average age of persons aged 18 years and over	37.71	44.98	40.69	40.45	1.59
Population Density	Number of inhabitants per square km	70.82	3898.53	664.76	214.91	1013.41
Alcohol and Drugs	Traffic offences: Alcohol and drug abuse (in 1,000s)	0.96	58.00	14.02	10.00	12.52
Speeding	Traffic offences: Speeding violations (in 1,000s)	7.00	709.00	160.29	89.03	158.49
License	Traffic offences: Driving without a licence or while disqualified (in 1,000s)	0.00	37.00	9.17	6.00	8.59
GDP	Growth rate of the real gross domestic product (in %)	-9.74	8.19	1.92	2.20	2.78

We also take account of different socio-economic variables. *Age Structure* is determined as the average age of all persons aged 18 and over (minimum driving age in Germany). This variable captures changes in the overall age structure of the population and, for instance, represents the demographic development of an ageing society. *Population Density* is determined as the number of inhabitants per square kilometre. We assume that in densely populated regions the general risk of accident involvement increases, although the risk for severe accidents might decrease due to lower average speeds as a consequence of increasing congestion. Furthermore, this study considers several factors increasing the risk of accident involvement that can be attributed to individual driving behaviour. Firstly, drunk driving and drug abuse is a classic parameter raising the crash risk and leading to serious accidents (Krüger and Vollrath, 2004; Elvik, 2013). *Alcohol and Drugs* is determined as the number of traffic offences due to alcohol and drug abuse. Secondly, speeding presumably increases the risk and severity of accidents. *Speeding* is measured as the number of traffic offences referring to speeding violations. Thirdly, persons operating vehicles without a license or while being disqualified, belong to a risk group of road users, who either have a lack of driving knowledge or who frequently violate traffic regulations. *License* is determined as the number of traffic offences due to driving without a valid license. Finally, the *GDP* growth rate is included to measure the impact of rising incomes and the level of economic activity.

Descriptive statistics for the variables are presented in Table 2. Note that the main reason for the large differences between the mean and the median in some variables, such as population density, is the fact that our sample includes the three city-states of Berlin, Hamburg and Bremen.

An analysis using panel data is commonly conducted by applying the popular differences-in-differences-estimator to identify policy effects. Since the toll was implemented simultaneously in all German regions, this is not possible in our case, given the lack of a control group. The identification of the policy effect is basically obtained by comparing the change in accident rates before and after the implementation of the HGV toll, while controlling for the covariates. Therefore, it is crucial to ensure that the differenced variables do not reveal any trend behaviour, in order to avoid spurious regression. In addition, it is important to account for potential time-constant unobserved heterogeneity between regions, resulting from distinctive climate conditions or differing cultural attitudes towards driving behaviour.

We employ two different estimation methods below in order to test the influence of tolling on accident rates with damage to persons both on non-tolled roads and on the overall road network. First, we provide a first differences (FD) estimator for panel data. The model can be written as:

$$\Delta AccidentRate_{it} = \lambda + \Delta Toll_t \delta + \Delta X_{it} \beta + \Delta u_{it}$$

$AccidentRate_{it}$ represents our variable measuring road accidents in region i at year t. $Toll_t$ is a dummy variable indicating the implementation of the road toll, X_{it} is the vector of time-varying covariates, u_{it} is an error term and λ is a common intercept measuring the average rate of change in the dependent variable.

Second, we provide a count regression model for panel data which is in line with Hausman et al. (1984).[8] Specifically, we employ a negative binomial model with an exponential mean function. This is appropriate since the data on accident rates is overdispersed, as we observe a variance that is about nine times larger than the mean. The conditional expectation of $AccidentRate_{it}$ is given by:

$$\mu_{it} = \alpha_i \exp(t\lambda + Toll_t \delta + X_{it} \beta)$$

Here, a_i represents the state-specific effect. We also include a linear time trend t to capture any trending behaviour in the dependent variables. The other covariates remain the same.

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[8] For a detailed description see Stroup (2012) or Cameron and Trivedi (2013).

In order to verify the efficiency of the FD estimator, compared to the usual within-estimator, we employ two tests. Firstly, a panel unit root test is applied to both accident rates. Since the time dimension of our data set is short, we use the procedure developed by Harris and Tzavalis (1999). As shown in Table 3, the different accident rates seem to follow a stochastic trend. In both cases, the trend vanishes after taking the first difference. Moreover, we employed the first-difference test proposed by Wooldridge (2010) to check if the errors of either the first differences or an analogously specified fixed effects model are serially correlated. This is not the case for both FD models and therefore implies the efficiency of the FD estimator.

Table 3. Test statistics

Test	Null Hypothesis	Accidents on all roads	Accidents on non-tolled roads
Harris-Tzavalis-Test			
Trend (Levels)	The panel contains a unit root and a time trend	0.2459	0.9936
Constant (Levels)	The panel contains a unit root	0.3607	0.0794
Trend (1. Difference)	The differenced panel contains a unit root and a time trend	0.0000	0.0000
Constant (1. Difference)	The differenced panel contains a unit root	0.0000	0.0000
Wooldridge-Test			
Errors of FE model	There is no serial correlation in the errors of the fixed effects model	0.0000	0.0000
Errors of FD model	There is no serial correlation in the errors of the first differences model	0.0721	0.3111

Notes: Reported values are p-values of the corresponding test.

4. Results

The estimation results are provided in Table 4.[9] The outcome of specifications 1 and 3 reveal that toll-induced rerouting leads to the expected increase of accident rates on non-tolled roads. However, this finding might be attributed to a simple traffic shift from tolled motorways to non-tolled alternative routes after the implementation of the toll. To identify whether further rerouting causes an increase in the total accident level and not merely a 'shift of accidents' between different road types, we also test specifications 2 and 4 using the accident rate for all road types as a dependent variable. We observe that our key variable *Toll* is also positive and significantly different from zero at the 1 per cent level in these specifications, indicating that road tolls have indeed an impact on the total number of severe accidents during our sample period. We can conclude from the results of the FD-model that 12.797 accidents per 100,000 inhabitants can be attributed to the introduction of the road toll in 2005. This corresponds to 3.07 per cent of all accidents with damage to persons and confirms the outcome of the negative binomial model indicating a rise in the number of accidents of 3.70 per cent after the introduction of the toll. Although the effect of tolling on accident rates seems to be not particularly large, we can conclude that external accident costs are most likely increasing due to the implementation of the HGV toll.

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[9] The software package STATA/SE 11 was used for all estimations of the negative binomial model. Estimations using the first-differences estimator were performed with the R 3.0.1 software package.

The coefficients for *Motorisation* are strictly positive, but only statistically significant at the 5 per cent level in the NB-model, indicating that an increasing degree of motorisation promotes higher accident rates. The coefficient associated with the *Motorway* share of the road network is negative in all specifications, as expected, but only statistically significant at the 10 per cent level in the FD-model. As outlined above, this points out that increasing proportions of motorway kilometres promote road safety, due to the safety-enhancing characteristics of this road category. The coefficient for the share of *HGV Traffic* is consistently positive, which is in line with the assumption that higher shares of heavy goods vehicles could lead to increasing numbers of severe accidents involving injuries and fatalities. However, we do not observe a significant influence during our sample period.

Table 4. Estimation results

	First differences		**Negative binomial**	
Dependent variable: damage to persons on…	non-tolled roads (1)	all roads (2)	non-tolled roads (3)	all roads (4)
Intercept	-6.222***	-6.705***	-6.40857***	-6.41148***
	(2.316)	(2.462)	(0.42360)	(0.41775)
Time trend	-	-	-0.01495***	-0.01494***
			(0.00357)	(0.00358)
Transport Variables				
Toll	11.795***	12.797***	0.03853***	0.03702***
	(2.647)	(2.854)	(0.01007)	(0.00954)
Motorways	-4.048*	-3.618*	-0.00793	-0.00764
	(2.082)	(1.953)	(0.00606)	(0.00598)
Motorisation	0.271	0.222	0.00139**	0.00101
	(0.345)	(0.377)	(0.00069)	(0.00066)
HGV Traffic.mpr	-	1.750	-	0.00435
		(1.083)		(0.00353)
HGV Traffic.pr	1.614	-	0.00046	-
	(1.073)		(0.00346)	
Socio-Economic Variables				
GDP	-1.121***	-1.003***	-0.00202**	-0.00174**
	(0.237)	(0.248)	(0.00086)	(0.00085)
Age Structure	-22.524***	-22.948***	-0.06047***	-0.05517***
	(7.235)	(8.426)	(0.01010)	(0.00971)
Population Density	-0.489***	-0.553***	0.00011	0.00009
	(0.115)	(0.122)	(0.00019)	(0.00019)
Alcohol and Drugs	0.045	-0.017	0.00015	0.00012
	(0.119)	(0.130)	(0.00038)	(0.00037)
Speeding	0.025	0.022	0.00004	0.00001
	(0.026)	(0.028)	(0.00005)	(0.00005)
License	0.300**	0.334***	0.00146***	0.00157***
	(0.127)	(0.124)	(0.00045)	(0.00043)
No. of obs.	171	171	171	171
No. of regions	16	16	16	16
R^2	0.2137	0.1972	-	-
F-Test	0.000***	0.000***	-	-
Hausman-Test	119.49***	89.46***	-	-
LR-Test χ^2	-	-	332.01***	348.78***
Log-likelihood	-	-	-1161.54	-1166.29

Notes: In all estimations, robust standard errors were used to account for heteroskedasticity and serial correlation. In the negative binomial model all coefficients reported (except the intercept) are semi-elasticities. Standard errors are reported in parenthesis.
*** Significant at the 1% level.
** Idem, 5%.
* Idem, 10%.

The coefficient for *Age Structure* is negative and significant at the 1 per cent level in all specifications. This development contributes to improving road safety that can be essentially attributed to demographic changes in Germany. On one hand, the proportion of the young population gradually decreases. This age group is especially prone to accident involvement, because of their relatively limited practical driving experience and the corresponding misperception of driving risks (see, for example, Lourens et al., 1999; Statistisches Bundesamt, 2013a). On the other hand, the share of older people in the total population continually increases, which contributes to a decreasing number of accidents. As stated by Statistisches Bundesamt (2013b), this is not due to the larger and longer driving experience but to a disproportionally low accident involvement of older people that can be attributed to a generally lower mobility level in this age group.

We also observe that the coefficient for *License* is positive and significant at the 1 and 5 per cent level in all specifications, indicating that this high-risk group of road users is associated with more severe accidents. The coefficients of the other variables that can be attributed to individual driving behaviour, *Alcohol and Drug* abuse, as well as to *Speeding* predominantly yield the expected signs but are insignificant. The results of the FD-model also show that densely populated regions are associated with a decreasing number of severe accidents, as the coefficient for *Population Density* is negative and significant at the 1 per cent level for both FD-specifications. This might be attributed to lower average speeds as a consequence of increasing congestion in metropolitan areas. However, the results of the NB-model do not appear to support this presumption. The coefficients of the other variables are significant and yield the expected signs.

It should be noted, however, that our study is limited to calculations based on aggregated data. Therefore, we basically analyse a microeconomic problem (route level) from a macroeconomic perspective (NUTS-1 level), as done previously by Albalate and Bel (2012). The individual-road treatment effect can be substantial for some roads, but zero for others. Additionally, if the fraction of roads with zero effects is large, the average effect will be small, despite the fact that there may be scope for policy intervention. Unfortunately, the available data and consequently the chosen model framework do not enable the isolation of severely affected roads. Nonetheless, we are confident that our analysis reveals the safety outcomes resulting from road charges at the aggregate level. Therefore, we expect that the toll implementation in Germany has indeed caused unintended spillovers.

5. Policy implications

The results of our analysis are of fundamental importance for policy makers (not only in Germany) and in line with the main findings by Albalate (2011), Albalate and Bel (2012) and Swan and Belzer (2013). We observe an impact of road toll implementation on accident rates that can be attributed to negative spillover effects on non-tolled alternative roads. Theoretically, policy makers can use different strategies to cope with this problem, but not all measures are applicable due to legal restrictions:[10]

Price incentives: Second-best tolls, as proposed by Verhoef (1996), account for external costs produced on tolled roads, but also consider the spillover effects generated on adjacent alternative tollfree roads, including additional accident costs. If tolling produces traffic diversion and

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[10] We use the classification proposed by Kummer and Nagl (2005).

subsequent losses of welfare due to overutilisation or higher safety risks on tollfree roads, toll tariffs should be lowered on affected routes. Accordingly, the optimal tariff can be found by constructing a price differentiation scheme based on the price elasticity of demand. This approach reduces the incentives for rat running, and consequently promotes road safety. Another alternative is to extend the charging system by including all road categories within the total network to prevent rerouting effects. Accordingly, the incentives to use alternative routes strongly decline ceteris paribus[11] (but depend on the actual toll rates for different road categories), because drivers will follow a strategy of efficient routing, as in a regime without tolls. The current European legislation is not intended to permit the implementation of network-wide road tolls. Therefore, this type of charging cannot be found within the European Union.[12] Nevertheless, international traffic diversion still may be of relevance, even if national rerouting is not expected. In such cases, the harmonisation of toll systems and tariffs in neighbouring regions or states may help to reduce rerouting traffic (Kummer and Nagl, 2005).

In Germany, law (BFStrMG) permits the public authorities to expand the toll regime if particular roads are severely affected by diverted traffic. However, this measure could lead not only to the intended re-rerouting onto motorways, but also to further traffic-diversion effects onto subsidiary roads, depending on the quality of adjacent free alternative roads and the related additional fuel and time costs. Moreover, traffic that originally intended to use the previously tollfree roads could also be diverted. As a result of the relatively low labour costs in Eastern Europe, in particular, hauliers from these countries might accept more time consuming trips (Wieland, 2005). This should not be neglected, due to Germany's central location in Europe and its role as a transit country.[13] As we have seen, a first extension of the German HGV toll scheme onto three federal road links (about 42 kilometres) in 2007 did not achieve a significant decline in traffic-diversion (Deutscher Bundestag, 2013).

Legal interventions: The implementation of legal measures, such as (temporary) traffic prohibitions and restrictions for different kinds of vehicle categories, potentially prevents drivers from using alternative toll free roads. However, this might have a substantial impact on the affected regions, regarding accessibility and economic potential. Furthermore, enforcement activities come at a cost for road users and governmental authorities (Kummer and Nagl, 2005). Nevertheless, legal measures are widely applied in Austria and Germany (Rothengatter, 2005; Deutscher Bundestag, 2013).

Infrastructural measures: Adjustments to infrastructure can further reduce rat running effects. Improving the quality of tolled roads might reduce the rerouting potential, provided that the benefits generated are substantial. Moreover, reducing the quality of alternative tollfree roads may have the opposite effect, causing re-rerouting onto better quality toll roads. However, this measure is costly and also produces negative economic effects for the affected regions (Kummer and Nagl, 2005). Furthermore, the quality improvement of safety-critical road sections could help to reduce the accident level. Although such a measure does not affect rat running behaviour and, therefore, does not imply a solution to the underlying problem. However, the realisation of construction measures comes at high investment costs compared to the implementation of price incentives or legal measures. Therefore, a prior cost-benefit analysis is strictly necessary, in order to ensure the effectiveness and efficiency of the available measures.

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[11] Other policy measures may also influence traffic diversion. See, for example, Rapp and Balmer (2003), describing the practice of weight limit constraints for HGV in Switzerland.

[12] Switzerland is the only country with network-wide road tolls.

[13] In 2010, the share of foreign HGV traffic (in tonne-kilometres) was 35% (BGL, 2012).

6. Conclusion

The purpose of this paper is to identify the impacts of the implementation of the German HGV toll and subsequent rat running effects on road safety outcomes. For our analysis, we use panel data based on German NUTS-1 regions for the period between 2000 and 2010. Our results show that tolling has a significant influence on the number of severe accidents which cause injuries and fatalities. We observe both, a shift of accidents to alternative non-tolled roads, but also an increase of the total accident level. Thus we gain new insights into the spillover effects produced by a large-scale distance-related toll system that is limited to heavy goods vehicles and has been solely implemented on state-owned road infrastructure. Therefore, policy makers should not only be aware of the traffic diversion problem, but also of the corresponding safety risks associated with different types of tolling systems.

Countermeasures to suppress traffic-diversion effects, as mentioned above, can most appropriately be implemented, when the costs of toll-induced spillovers (e.g. additional congestion, noise and accident costs) are known in detail. Theoretically, the use of price incentives, such as second-best tolls which account for external costs in the total road network, constitutes the most promising approach for realising efficient outcomes from the welfare perspective. However, restrictions of European law, both regarding the expansion of toll schemes and the internalisation of external accident costs, as well as the current focus of tariffs on infrastructure cost recovery, which ignores most of the external costs, limit the application of price incentives. Furthermore, it should be noted that, for example, network-wide tolling might reduce safety risks induced by rat running, but also implies higher transport costs, leading to competitive disadvantages for domestic transport sectors. For this reason, the harmonisation of toll systems should be an important European transport-policy objective, in order to prevent both distortions of competition and increases in international traffic diversion. Nevertheless, the decisions of policy makers should be based on economic criteria and favour the most welfare-enhancing alternative. Therefore, it is important to determine and reflect on the costs and benefits of all available countermeasures. Ignoring the delicate problem of increasing safety risks only seems to be at all acceptable, if the implementation of a welfare-benefiting policy is not feasible.

Finally, we would like to point out two approaches for future research. Firstly, the estimation of the toll effect basically focuses on the year of toll implementation. Since then, German policy makers have addressed the rat running problem by using legal interventions, such as traffic restrictions, and by expanding HGV tolls onto federal roads. However, our analytical model is not able to identify safety effects resulting from these policy measures. But we can observe that pricing still ignores external safety costs and therefore fails to meet the criterion of second-best efficiency. Moreover, efficiency outcomes of legal interventions are uncertain from a welfare and safety-enhancing perspective. Secondly, since disaggregated data is not available, an analysis of the safety effects of toll implementation at the micro-level is beyond the scope of this paper. Yet, it is an important approach for further research, in order to obtain a better understanding of the relationships between tolls, traffic diversion and road safety.

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