Doshisha University

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ITEC Working Paper Series

17-02

June 2017

ITEC
Institute for Technology, Enterprise and Competitiveness

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Institute for Technology, Enterprise and Competitiveness,
Doshisha University
Working Paper 17-02

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Keywords: Automated driving systems, lane-departure accidents, safety regulations, mandatory installation, economic incentives, optimal market-diffusion rates

JEL codes: C51, C63, D62, R41

The author's fields of expertise:

Public economics, transportation economics

Abstract:

In this paper, we analyse the benefits derived from the avoidance of traffic-accident losses through the use of lane-departure prevention technologies. We present a formulation that divides these benefits into two categories—*benefit derived from system users* and *benefit derived from secondary parties*—and estimate the magnitude of both types of benefits using data from the Japan Traffic Accidents General Database (macro). Based on this analysis, we estimate several quantities of relevance for policymaking: the optimal rate of market diffusion for lane-departure prevention technology devices, the magnitude of the economic incentive needed to achieve this optimal market-diffusion rate, and the benefits of regulatory policies that mandate the installation of system devices, including both benefits for vehicles subject to the mandate and those for other vehicles. The primary new insights obtained within the scope of our analysis are two. First, the magnitude of the *benefit derived from secondary parties* accounted for over 20% of the marginal social benefit. It is highly likely that the amount far exceeding 20 % of the price of lane-departure prevention device will need to be economically incentivized to achieve optimal market-diffusion rates for these systems. Second, Japanese safety regulations for road vehicles call for mandatory installation of lane-departure warning systems on new trucks at over 3.5 ton gross vehicle weight and new buses with capacity for 10 or more passengers (stepwise introduction from heavy vehicles); our analysis finds it appropriate to assign high priority for mandatory installation to all categories of standard/small trucks.

Acknowledgements

The preparation of this manuscript was supported by JSPS Grants-In-Aid for Scientific Research (*Kakenhi*) #25281071 ("Study of Policies to Promote the Market Diffusion of Next-generation Vehicles and Their Global Benefits") and #16K12830 ("Social-welfare Analysis of Automated Driving Systems"). In addition, this paper is a result of the visiting researcher program of the Institute for Traffic Accident Research and Data Analysis (ITARDA). The views expressed in this paper are the author's own and do not reflect the view of ITARDA.

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1. Introduction

Many studies have been conducted with regard to the impacts of Advanced Driving Assistance Systems (ADAS) (e.g. Abe, 2008; Anderson et al. 2012; Fitch et al., 2008; Jeong and Oh, 2015, Jermakian, 2012; Kusano et al., 2014; Kuehn et al., 2009; Sugimoto and Sauer, 2005). Among them, Fitch et al. (2008) studied the effect of installing forward-collision warning (FCW) alarms on heavy vehicles and reported that these systems can reduce rear-end collisions by 21%. Jeong and Oh (2015) conducted an analysis using a microscopic traffic simulator and found that active vehicle safety systems (AVSSs), including adaptive cruise control (ACC), can—under certain conditions—reduce rear-end collisions by 78.8%. With regard to lane-departure accidents, Abe (2008) conducted experiments in a driving simulator to measure the impact of lane-departure warnings (LDW) on the frequency with which drivers deviated from their lanes by more than a certain reference threshold and the total duration of these lane departures. The results showed that LDW devices have a significant impact on preventing rightward lane departures. Kusano (2014) quantified the number of crashes and seriously injured drivers that could have been prevented in the United States in 2012 had all vehicles been equipped with LDW and concluded that LDW could potentially prevent 28.9 percent of all road departure crashes caused by the driver drifting out of his or her lane.

Several studies investigate the economic aspect of these technologies—addressing questions such as the economic benefits of ADAS. For example, Murray et al. (2009) evaluated costs and benefits for industry associated with FCW that can reduce large truck rear-end crashes found that a FCW system in large trucks could provide a more than a dollar back in benefits, ranging from $1.33 to $7.22 for every dollar spent on the system. Li and Kockelman (2016) found that eleven CAV technologies, such as FCW, when combined with Cooperative Adaptive Cruise Control, and Cooperative Intersection Collision Avoidance Systems, can save Americans $76 billion each year (along with almost 740,000 functional-life-years saved per year) functional-life-years saved per year). Previous studies, however, suffer from the drawback of treating the diffusion rate of collision-prevention devices exogenously. In such an approach, it is not possible to address the question of what types of policies will be effective in stimulating the diffusion of the technology through the market

In this paper, working within the context of the considerations outlined above, we focus on the particular case of lane-departure accidents; we formulate and compute a measure of the economic benefits derived from the use of systems to prevent this type of accident. Based on our findings, we estimate several quantities of relevance for policymaking: the optimal rates of market diffusion for lane-departure prevention technology devices, the magnitude of the economic incentives needed to achieve these optimal market-diffusion rate, and the benefits of regulatory policies that mandate the installation of system devices, including benefits for vehicles subject to the mandate and benefits for other vehicles.

The remainder of this paper is organized as follows. In Section 2, we discuss the types of accidents and technologies we study and the associated benefits we seek to estimate. In Section 3, we discuss our methods for computing benefits and the data we use in our analysis. In Section 4, we use data from the Japan Traffic Accidents General Database, J-TAD (macro), maintained by Japan’s Institute for Traffic Accident Research and Data Analysis (ITARDA) to estimate the frequency of the lane-departure accidents we study in this paper and the losses associated with these accidents. In Section 5, we discuss the marginal benefit derived from lane-departure prevention technologies, the optimal market-diffusion rates for these technologies, and the economic incentives needed to achieve these rates. In Section 6, we discuss the impact of regulatory policies that mandate the installation of lane-departure prevention devices.

2. The subjects of our analysis

In this section, we specify the types of accidents and accident-prevention technologies we consider and the types of benefits we seek to quantify.

2.1 The types of accidents and prevention technologies we consider

The analysis of this paper focuses on technologies for preventing lane-departure collisions and the accidents that may be avoided through the use of these technologies. At present, two technologies for preventing lane-departure collisions are commercially available: (a) lane-departure warning systems, which detect when a vehicle is close to deviating from its lane and sound an audible warning with an alarm display in that case, and (b) lane-maintenance assistance systems, which assist steering by anticipating a vehicle's deviation from its lane and shifting the direction of the vehicle to restore it to a proper position within the lane. To detect lane departures, these technologies make use of resources such as images captured by C-MOS or CCD cameras installed in vehicles and/or GPS location data.

What types of accidents are avoided through the use of lane-departure accident prevention systems? The classification scheme used by Japan's Cabinet Office (2015) considers a total of 255 accident sectors. For the various sectors of accidents in this classification scheme, Japan's Cabinet Office (2015) determines the number of cases in which installation of lane-departure prevention technologies could have prevented an accident from resulting in death. In the analysis presented in the remainder of this paper, we use extract conditions listed in table 1 prepared by author in reference to Japan's Cabinet Office (2015) with 2015 data from Japan Traffic Accidents General Database, J-TAD (macro) to quantify accident instances and fatalities. Human factor in Table 1 is different extract condition than Japan's Cabinet Office (2015). For the purposes of this study, we assume that the installation of lane-departure prevention devices is 100% effective in averting accidents of the types identified above; we separate the benefits obtained through the use of these systems into *benefit derived from system users* and *benefit derived from secondary parties* as described in detail below, and we present a formulation that allows us quantify the magnitude of these benefits.

Because of our unrealistic assumption regarding effectiveness, the analytical results presented in this paper do not accurately represent the actual benefits arising from the technologies in question. Despite this limitation, our study nonetheless furnishes quantitative answers to several questions of major importance for the policy-making process, including (1) the relative magnitude of externality benefits as a fraction of all benefits, and (2) the differing magnitudes of the benefits arising from mandatory installation policies that target different types of vehicles.

On the other hand, the scope of our analysis in this study does not include vehicle-pedestrian accidents. The reason for this is that the data on vehicle-pedestrian accidents present in the Cabinet Office (2015) classification is incomplete, and we judge it to be insufficient to justify assumptions as to whether or not lane-departure prevention technologies could have prevented all vehicle-pedestrian accidents of a given type from leading to fatality.

In what follows, the primary party in a vehicle-vehicle accident is the driver or vehicle judged to be more at fault for the accident (or, if both parties are equally at fault, the driver or vehicle for whom personal bodily injuries are less severe). In the case of lane-departure accidents the primary party is the driver or vehicle who departed their lane. In a single-vehicle accident, the primary party is the party or vehicle responsible for causing the accident. The secondary party in a vehicle-vehicle accident is the driver or vehicle judged to be less at fault. In lane-departure accidents the secondary party is the driver or vehicle who collides with the lane-departing vehicle.

Table 1 Data extract conditions for lane-departure accidents

Type of accident	Type of road	On-road setting	Detailed type of accident	State of motion of the primary party	Direction of progress of the secondary party	Human factor causing accident
Vehicle-vehicle	General road	Basic road section including neighborhood of intersection	Head-on collison	Starting to move, proceeding in the forward direction, over-take, changing routes	Oncoming	Primary party's delay of detection due to not looking forward carefully, Primary party's mistake in Judgement pertaining to road shape, Primary party's mistake in steering.
			Accident during passing			
	Expressway		Collisions or contact accident with on coming vehicle	–	–	
Single-vehicle	General road and Expressway		–	Starting to move, proceeding in the forward direction, over-take, changing routes	–	

Note 1: Not looking ahead carefully includes drowsy driving and inattentive driving.
Note 2: The data which satisfy one of conditions in each column at the same time are extracted.

2.2 The benefits we calculate

As noted above, the benefits we seek to quantify are those derived from the avoidance of traffic accidents and the associated losses. According to the Cabinet Office of Japanese Government (2012), losses associated with traffic accidents may be separated into monetary losses and non-monetary losses. Monetary losses consist of personal losses (e.g. medical expenses, lost wages due to missed work), material losses (e.g. damage to vehicles or structures requiring repairs), losses incurred by corporate entities (reduction of added value due to missed work, death, or residual disability), and losses incurred by various public institutions (e.g. emergency transportation costs and costs of accident handling by police). On the other hand, non-monetary losses include physical or emotional suffering on the part of victims stemming from personal bodily harm or damage to material property suffered because of a road traffic accident; emotional pain and suffering experienced by the families and friends of victims; psychological burdens experienced by the persons responsible for causing the accident and their families and friends; and all other losses other than consumption or destruction of monetary resources and loss of performance. Among these various types of damage, Japan's Cabinet Office (2012) establishes values for losses based on the pain and suffering experienced by the actual victims of accidents themselves, treating deaths and injuries as separate categories.

The avoidance of non-monetary losses is a benefit enjoyed directly by users through the installation of accident-prevention system devices. On the other hand, the benefits associated with the avoidance of monetary losses are enjoyed by a variety of economic entities. For example, among monetary losses, quantities equivalent to personal losses and material losses are covered by damage insurance. Thus, unless installations are accompanied by discounts for insurance premiums, the avoidance of personal losses will be a benefit for the insurance company, not for the user of the prevention-technology device. Similarly, the avoidance of losses by corporate entities or various types of public institution also constitute benefits enjoyed by entities other than device users. Thus, there are various entities to whom benefits accrue. Nonetheless, for the purposes of this article, we do not address these questions in detail, instead defining the *benefit derived from system users* to be the sum of the *benefits derived from system users* from the avoidance of monetary and non-monetary losses associated with accidents caused by lane departures in which the user was the primary party. This includes the benefits enjoyed by fellow passengers in the primary vehicle due to the avoidance of monetary and non-monetary losses. Meanwhile, for vehicle-vehicle accidents, the avoidance of an accident by a primary system user results in reduced traffic-accident losses for secondary parties as well. In this paper, we refer to the sum of the benefits to secondary parties resulting from the avoidance of monetary and non-monetary losses as the *benefit derived from secondary parties*. This includes any benefits derived from the avoidance of monetary and non-monetary losses by fellow passengers in the secondary party's vehicles. Note that *benefit derived from secondary parties* are enjoyed both by vehicles equipped with accident-prevention devices and by vehicles not equipped with the devices. I addition, non-monetary losses in this paper do not include emotional pain and suffering experienced by the families and friends of victims and psychological burdens experienced by the persons responsible for causing the accident and their families and friends.

3. Methods for computing benefit

In this section, we discuss the data sources and computational methods we use to compute benefits within the analytical framework discussed above.

3.1 Computational methods

The greater the distance traveled by a driver, the greater the driver's likelihood of experiencing a traffic accident, and thus the greater the by the installation of an accident-prevention technology. Based on this premise, we use the following methods to compute benefits.

3.1.1 Vehicle-vehicle accidents

For user i of vehicle type k, we define the benefit derived from the adoption of a lane-departure prevention technology—termed the *benefit derived from system users* and denoted $UI_{i,k}$—in the form

$$UI_{i,k} = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t} (d_{i,k} * \sum_{l=1}^{m} (\sum_{j=1}^{n_l} d_{j,l} * a_{k,l} * u_{k,l})) . \tag{1}$$

Here $d_{i,k}$ is the annual distance traveled by user i of vehicle type k, for which we assume a certain probability distribution. n_l is the number of automobile of vehicle type l. $a_{k,l}$ is computed by dividing the annual number of lane-departure-induced vehicle-vehicle accidents in which the primary and secondary parties are respectively of types k and l by the product of the total annual distance traveled by vehicles of types k and l. $u_{k,l}$ is the sum of the monetary and non-monetary losses per accident experienced by the primary party (including fellow passengers in the primary party) due to lane-departure-induced vehicle-vehicle accidents in which the primary and secondary parties are respectively of types k and l. m is the number of vehicle types. In this paper, we use the 7 vehicle categories of Japan's Road Transport Vehicle Act: standard/small buses, standard/small passenger vehicles for private use, standard/small passenger vehicles for commercial use (taxis), mini passenger vehicles, standard/small trucks at over 3.5 ton GVW (gross vehicle weight), standard/small trucks at 3.5 ton or less GVW and mini, and two-wheel vehicles (including light two-wheel vehicles). t_k is the average number of years of use for vehicle type k, and γ is the discount rate, for which we use the value of 0.04.

Next, we define the magnitude of the benefits derived from other vehicles due to the installation, by user i of vehicle type k, of a lane-departure prevention system—

termed the *benefit derived from secondary parties* and denoted $E_{i,k}$ —in the form

$$E_{i,k} = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t} (d_{i,k} * \sum_{l=1}^{m} (\sum_{j=1}^{n_l} d_{j,l} * a_{k,l} * v_{k,l})) \tag{2}$$

Here $v_{k,l}$ is the sum of the monetary and non-monetary losses per accident experienced by the secondary party and its fellow passengers due to lane-departure-induced vehicle-vehicle accidents in which the primary and secondary parties are respectively of types k and l.

3.1.2 Single-vehicle accidents

For the case of single-vehicle accidents, the *benefit derived from system users* $US_{i,k}$ is defined to be the benefit derived by user i of vehicle type k from the adoption of a lane-departure prevention technology, given by

$$US_{i,k} = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t} (d_{i,k} * b_k * w_k) . \tag{3}$$

Here b_k is the annual number of single-vehicle accidents resulting from lane departures for vehicle type k divided by the total annual travel distance for that vehicle type. w_k is the total of all monetary and non-monetary damages per accident for single-vehicle accidents associated with lane departures for vehicle type k .

3.2 Data

We next discuss the data values we used for the various variable quantities in the equations above. Our values generally correspond to data for the year 2015.

3.2.1 Numbers of automobiles and annual travel distances

First, we obtain data from the statistics provided by the Japan's Automobile Inspection & Registration Information Association for the numbers of vehicles of various types owned at the end of June, 2015.

Next, assuming that travel distances for standard/small passenger vehicles and mini passenger vehicles will be distributed according to a log-normal distribution, we use monthly travel-distance data from the Japan Automobile Manufacturers Association (2016) to determine the average and median monthly travel distances for 2015, then use these to compute the parameters in the log-normal distribution of annual travel distances.

3.2.2 Numbers of traffic accidents and fatalities

As discussed in Section 2.1, to identify the types of accidents that may be avoided by the use of lane-departure prevention technologies, we use the extract conditions listed in Table 1 together with 2015 data from the J-TAD (macro) to compute numbers of accidents and fatalities. In addition to counting fatalities, we also counted the total number of all accidents involving human injury that may be avoided. On the other hand, the range of accidents we consider in this paper is more narrow than that of the 2015 Cabinet Office classification; specifically, for vehicle-vehicle accidents we restrict our analysis to cases in which the primary vehicle was a four-wheel vehicle and the secondary vehicle was a four-wheel or two-wheel vehicle (not including bicycles), while for single-vehicle accidents we consider only cases in which the primary vehicle was a four-wheel vehicle. This is because lane-departure prevention technologies are designed primarily for four-wheel vehicles.

3.2.3 Base units for monetary and non-monetary losses by types of bodily injuries

Table 2 lists monetary and non-monetary losses per individual victim for personal bodily injuries of various degrees of severity. Here we have used 2009 values as established by Japan’s Cabinet Office (2012) and adjusted to 2015 yen amounts using a GDP-deflator. Here we note that, whereas the Cabinet Office (2012) classifies personal bodily injuries into three severity classes—death, residual disability, and injury—the J-TAD (macro) uses a different set of three categories: death, serious injury, and slight injury. Here we have performed calculations on the assumption that ITARDA’s categories of serious injury and slight injury correspond respectively to the residual disability and injury categories in the Cabinet Office classification. Table 2 reflects these results.

3.2.4 Average vehicle life expectancy

Lane-departure prevention technologies are installed in newly purchased vehicles, and the benefit derived from their use persists throughout the useful lifetime of the vehicle. Thus, the number of years a vehicle is used is an important input to the computation of benefit. For this reason, we use the following method to determine the average life expectancy for each of the various vehicle types—with the exception of standard/small passenger vehicles for commercial use to which this method does not apply.

First, we assume that 1) the maximum number of years a vehicle may be used—dating from the initial vehicle registration—is 40.5 years; 2) the rate at which vehicles are discarded obeys a Weibull distribution parameterized by the number of years of vehicle use dating from initial registration. Then the number of vehicles owned at the end of year *t* is a function of the number of vehicles sold over the past 41 years:

$$STOCK_t = SALES_t * \exp(-(\frac{0.5+0}{\eta})^m) + SALES_{t-1} * \exp(-(\frac{0.5+1}{\eta})^m) +$$
$$.................................+ SALES_{t-39} * \exp(-(\frac{0.5+39}{\eta})^m) + SALES_{t-40} * \exp(-(\frac{0.5+40}{\eta})^m)$$

Here $STOCK_t$ is the number of vehicles owned at the end of year t. $SALES_t$ is the number of new vehicles registered during year t. η and m are respectively the scale and shape parameters in the Weibull distribution. Here we assume a value of m =3, then determine for each vehicle type the value of η that minimizes the error in the estimated number of vehicles owned in 2015, using 2015 data for the number of vehicles owned of each type and data from 1975 to 2015 on the numbers of new-vehicle registrations for vehicles of each type. Then, from the values of η thus obtained, we determine the average number of years of vehicle use. For our estimates, we used data on numbers of vehicles owned and new vehicle registrations taken from the *World Motor Vehicle Statistics* prepared by the Japan Automobile Manufacturers Association and the statistics provided by the Japan's Automobile Inspection & Registration Information Association. Table 3 lists the results of our calculations. For standard/small- passenger vehicles for commercial use (taxis), the calculations outlined above cannot be performed; instead, we determined average life expectancies for such vehicles based on industrial hearings.

4. Frequency of lane-departure accidents and associated losses

In this section, we use data from the J-TAD (macro) to compute numbers of accidents and total associated loss amounts for accidents caused by lane-departures. We will separately consider the cases of vehicle-vehicle and single-vehicle accidents.

4.1. Vehicle-vehicle accidents

Tables 4, 5, 6, and 7 list statistics on vehicle-vehicle accidents caused by lane violations in 2015—numbers of accidents, losses per accident, and total losses—as computed using the methods and data discussed in Sections 2.1, 3.1 and 3.2.

First, Table 4 presents data on accident counts in the form of a matrix indexed by primary and secondary party's vehicle type. The number of accidents is 5,214 and accidents in which the primary vehicle is a standard/small passenger vehicle for private use or a mini passenger vehicle account for approximately 83% of the total accidents. Table 5 presents the amount of the losses per accident sustained by the primary party's vehicle (including its fellow passengers) [$u_{k,l}$ in Eq. (1)], again in the form of a matrix indexed by vehicle type. Losses are computed by multiplying, for each bodily-injury severity class, the number of victims of injuries in that class by the base units for losses listed in Table 2. According to this calculation, on average each accident results in losses of 7,693 thousand yen. Comparing statistics for different vehicle types, we see that cases in which the secondary vehicle is a large vehicle (a standard/small bus or a standard/small truck at over 3.5 ton GVW) stand out for the large losses they produce. Next, considering the losses per accident incurred by secondary party's vehicle (including its fellow passengers) [$v_{k,l}$ in Eq. (2)] as tabulated in Table 6, we see that each accident results in an average loss of 5,703 thousand yen. Comparing results for different vehicle types, we see that cases in which the secondary vehicle is a two-wheel vehicle stand out for their relatively large losses. On the other hand, although losses are large for cases in which the primary vehicle is a truck at over 3.5 ton GVW and the secondary vehicle is a four-wheel vehicle, the differences between losses here are not as great as are found for losses sustained by the primary vehicle in cases where the secondary vehicle is a truck at over 3.5 ton GVW. Finally, from Table 7 we see that total accident-related losses incurred by primary and secondary parties and their fellow passengers for vehicle-vehicle accidents amount to 69,849 million yen; in analogy to what we found for the frequency of accidents, accidents in which the primary vehicle is a standard/small passenger vehicle for private use or a mini vehicle account for some 80 % of this total.

Table 2: Monetary losses for personal bodily injuries of various degrees of severity

(Thousand yen)

	Death	Serious Injury	Slight Injury
Monetary Losses	31,122	9,546	1,599
Non-monetary losses	210,326	8,479	234
Total	241,449	18,025	1,833

Source: Data taken from Japan Cabinet Office (2012) Table 6-4, "Loss amounts per individual victim (not excluding compensation for emotional suffering)" and multiplied by GDP deflator to convert to 2015 values.

Table 3: Weibull-distribution parameters and estimated mean vehicle life expectancies

Vehicle type		Weibull distribution: Shape parameter	Weibull distribution: Scale parameter	Estimation error	Average life expectancies
Standard/small buses		3.0	17.3	0.0	15.5
Passenger cars	Standard/small for private use	3.0	14.9	0.0	13.3
	Standard/small for commercial use	-	-	-	5.0
	Mini	3.0	17.7	0.0	15.9
Trucks	Standard/small at over 3.5 tonnes GVW	3.0	18.2	0.0	16.2
	Standard/small at 3.5 tonnes GVW or less, and mini	3.0	15.5	0.0	13.9
	Standard/small at 3.5 tonnes GVW or less	3.0	12.7	0.0	11.3
Mini (passenger vehicle and trucks)		3.0	18.2	0.0	16.2

Note 1: Average vehicle life expectancy for each of mini vehicles and standard/small trucks at 3.5 ton or less GVW are utilized in section 6.

Note 2: The "estimation error" is the absolute value of the difference between the estimated and actual number of vehicles owned, divided by the actual number of vehicles owned.

Table 4: Number of vehicle-vehicle accidents resulting from lane departures, arranged by vehicle type (2015)

Secondary party \ Primary Party		Buses: Standard and small	Passenger cars: Standard and small for private use	Passenger cars: Standard and small for commercial use	Passenger cars: Mini	Trucks: Standard and small at over 3.5 ton GVW	Trucks: Standard and small at 3.5 ton or less GVW and mini	Total
Buses	Standard and small	0	27	1	16	3	6	53
Passenger cars	Standard and small for private use	3	1,220	10	796	70	295	2,394
	Standard and small for commercial use	0	40	1	22	1	6	70
	Mini	5	635	7	579	33	220	1,479
Trucks	Standard and small at over 3.5 ton GVW	3	189	1	162	40	66	461
	Standard and small at 3.5 ton or less GVW and mini	3	280	1	288	21	103	696
Two-wheel vehicles		2	25	1	26	4	3	61
Total		16	2,416	22	1,889	172	699	5,214

Source: Prepared by the author using data from the J-TAD (macro)

Table 5: Losses per accident sustained by the primary party in vehicle-vehicle accidents caused by lane departures (2015)

（Thousand yen）

Secondary party \ Primary Party		Buses	Passenger cars			Trucks		Average
		Standard and small	Standard and small for private use	Standard and small for commercial use	Mini	Standard and small at over 3.5 tonnes GVW	Standard and small at 3.5 tonnes or less GVW and mini	
Buses	Standard and small	－	23,373	0	79,634	6,008	43,246	41,183
	Standard and small for private use	0	3,903	24,511	4,440	930	7,150	4,476
Passenger cars	Standard and small for commercial use	－	6,578	0	986	－	305	4,095
	Mini	367	2,442	524	2,309	0	5,263	2,739
Trucks	Standard and small at over 3.5 tonnes GVW	7,841	34,206	36,050	51,995	14,463	56,549	41,775
	Standard and small at 3.5 tonnes or less GVW and mini	611	2,591	0	6,937	858	8,453	5,192
Two-wheel vehicles		0	73	0	0	458	611	90
Average		1,699	5,960	12,947	8,781	3,962	11,635	7,693

Note: Values include losses incurred by fellow passengers in the primary parties' vehicles

Source: J-TAD (macro) and the base loss amounts of Table 2.

Table 6: Losses per accident sustained by the secondary party in vehicle-vehicle accidents caused by lane departures (2015)

（Thousand yen）

Secondary party \ Primary Party		Buses	Passenger cars			Trucks		Average
		Standard and small	Standard and small for private use	Standard and small for commercial use	Mini	Standard and small at over 3.5 tonnes GVW	Standard and small at 3.5 tonnes or less GVW and mini	
Buses	Standard and small	－	3,903	1,833	1,375	2,444	4,531	3,089
	Standard and small for private use	3,055	5,737	2,199	3,662	11,716	3,321	4,906
Passenger cars	Standard and small for commercial use	－	3,635	1,833	3,069	－	2,138	3,277
	Mini	1,466	9,227	1,833	5,652	7,508	4,972	7,095
Trucks	Standard and small at over 3.5 tonnes GVW	1,833	2,378	1,833	1,910	3,673	1,962	2,262
	Standard and small at 3.5 tonnes or less GVW and mini	7,230	7,463	1,833	7,048	15,818	7,152	7,489
Two-wheel vehicles		1,833	25,609	1,833	6,122	5,881	7,230	13,936
Average		2,959	6,742	1,999	4,645	9,184	4,294	5,703

Note and source: See those in Table 5.

Table 7: Total losses due to vehicle-vehicle accidents caused by lane departures (2015)

(Million yen)

Secondary party \ Primary Party		Buses: Standard and small	Passenger cars: Standard and small for private use	Passenger cars: Standard and small for commercial use	Passenger cars: Mini	Trucks: Standard and small at over 3.5 tonnes GVW	Trucks: Standard and small at 3.5 tonnes or less GVW and mini	Total
Buses	Standard and small	0	736	2	1,296	25	287	2,346
Passenger cars	Standard and small for private use	9	11,761	267	6,449	885	3,089	22,460
	Standard and small for commercial use	0	409	2	89	2	15	516
	Mini	9	7,409	16	4,609	248	2,252	14,544
Trucks	Standard and small at over 3.5 tonnes GVW	29	6,914	38	8,733	725	3,862	20,301
	Standard and small at 3.5 tonnes or less GVW and mini	24	2,815	2	4,028	350	1,607	8,826
Two-wheel vehicles		4	642	2	159	25	24	856
Total		75	30,687	329	25,363	2,261	11,134	69,849

Note and source: See those in Table 5.

4.2 Single-vehicle accidents

We next consider single-vehicle accidents caused by lane departures. Table 8 tabulates estimates of the number of such accidents, the losses per accident, and the total losses for all such accidents. Considering first the number of accidents, we find a total of 7,614 accidents; similar to what we found for vehicle-vehicle accidents, cases in which the primary vehicle was a standard/small passenger vehicle for private use or a mini vehicle account for some 70 % of this total. Next, on average each accident results in losses of 9,588 thousand yen. Here the differences between vehicle types are not particularly significant when compared with the case of vehicle-vehicle accidents, but one feature that stands out from the data is that losses per accident are smaller for vehicles that transport customers as passengers: standard/small buses and standard/small passenger vehicle for commercial use (taxis). Finally, total losses amount to 73,001 million yen, larger than the corresponding figure for vehicle-vehicle accidents.

Table 8: Numbers of accidents, losses per accident, and total losses for single-vehicle accidents caused by lane departures (2015)

Primary Party / Secondary party	Buses	Passenger cars			Trucks		Average or total of all types of vehicles
	Standard and small	Standard and small for private use	Standard and small for commercial use	Mini	Standard and small at over 3.5 tonnes GVW	Standard and small at 3.5 tonnes or less GVW and mini	
The number of accident	497	2,784	447	2,503	257	1,126	7,614
Losses per an acccident (thousand yen)	452	11,318	636	9,180	11,807	13,295	9,588
Losses (million yen)	225	31,510	284	22,978	3,034	14,970	73,001

Note and source: See those in Table 5

5. Marginal benefit and optimal market-diffusion rate for lane-departure prevention technologies

In this section, we interpret the reduction in accident-related losses due to avoidance of vehicle-to-vehicle or single-vehicle accidents stemming from lane departures as a benefit enjoyed by users of accident-prevention system devices, and we compute this benefit using Eqs. (1)-(3). We restrict our focus to passenger vehicles (specifically, two vehicle types: standard/small passenger vehicles for private use and mini vehicles).

Results of our calculations are plotted in Figure 1. As discussed in Section 2.2, the marginal value of *benefit derived from system users* is the sum of the monetary and non-monetary losses that were avoided, during the average life expectancy of a single vehicle, through the use of an accident-prevention system device to avert accidents involving this vehicle as the primary party’s vehicle. Figure 1 plots, in descending order, this benefit versus the market-diffusion rate for the system devices; a value of 1 on the horizontal axis corresponds to the case in which all passenger vehicles are equipped with the devices. Ordinarily, this would be simply the consumer demand curve (curve of marginal private benefit); however, as noted above, in this case the *benefit derived from system users* includes benefit enjoyed by non-users, and thus this curve is not the same as the demand curve. On the other hand, the curve of marginal social benefit is the sum of the marginal value of *benefit derived from system users* and that *derived from secondary parties*; the value of this curve at a given market-diffusion rate measures the magnitude of the benefit to society as a whole from a single marginal vehicle (the vehicle for which the benefit is smallest at the given market-diffusion rate) installing a system device.

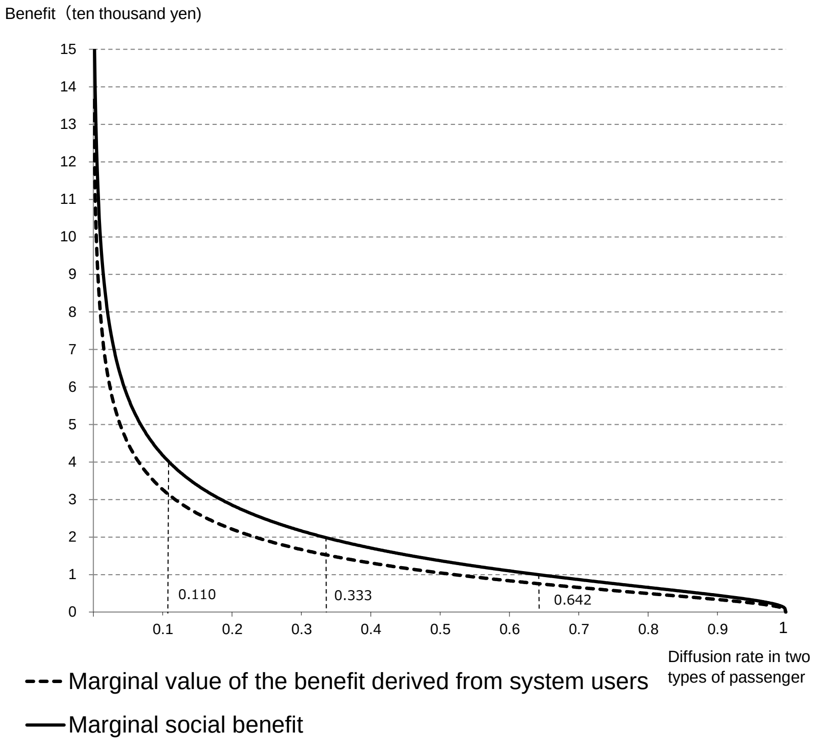
Next, we discuss our estimates of the optimal market-diffusion rates for accident-prevention system devices. The optimal market-diffusion rate is the point at which the curve of marginal social intersects the curve of social cost required to produce a lane-departure prevention device. For several reasons—including the facts that the standalone cost of lane-departure prevention devices may not be clearly indicated in catalogs and other sources, and that the devices may offer additional functionality beyond lane-departure prevention—it is difficult to obtain accurate estimates of the social cost of producing devices with only lane-departure-prevention functionality alone. For this reason, we performed trial calculations of optimal market-diffusion rates for three values—40 thousand yen, 20 thousand yen, and 10 thousand yen—of the social cost of producing devices with lane-departure-prevention functionality. We choose these values because the market price of post-manufacturer drive-recording devices with lane-departure warning functionality is on the order of 10,000–40,000 yen. The results of our calculations indicated that the optimal market-diffusion rates at social-cost values of 40, 20, and 10 thousand yen were respectively 11.0 %, 33.3 %, and 64.2 %.

To achieve these optimal market-diffusion rates requires economic incentives such as cost subsidies equal to the difference between the marginal curves of social and private benefit. As noted above, the marginal private benefit is unclear, and thus we investigated the difference between the marginal social benefit and the marginal value of *benefit derived from system users*—that is, the *benefit derived from secondary parties*—for each of three optimal market-diffusion rates. Our results indicated that the magnitude of the *benefit derived from secondary party* accounted for 21.9 %, 23.1 %, and 24.1 % of the marginal social benefit at market-diffusion rates of 11.0 %, 33.3 %, and 64.2 % respectively.

6. Impact of policies to mandate installation of lane-departure prevention devices

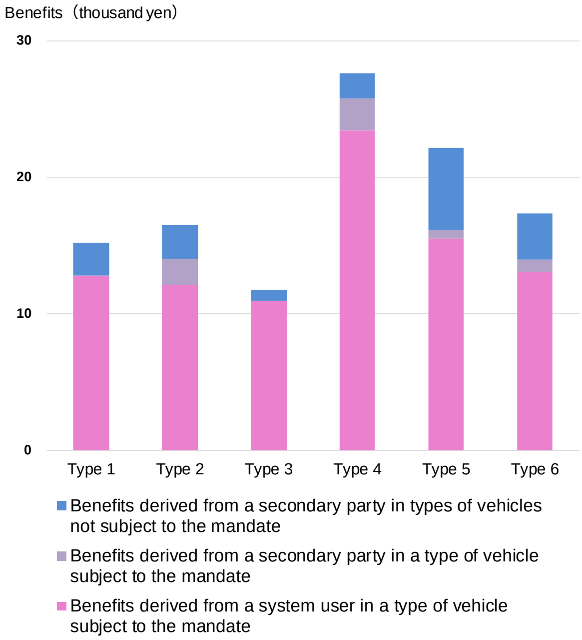
Japanese safety regulations for road transport vehicles call for mandatory installation of lane-departure warning devices on new trucks at over 3.5 ton GVW and new buses with capacity for 10 or more passengers (stepwise introduction from heavy vehicles). What will be the impact of this strengthening of safety regulations?

Assuming that only some types of vehicles are subject to installation mandates, Figure 2 shows the impact of each single vehicle of a given type—both on itself and on other vehicles—for the case in which all vehicles in the categories subject to the mandate are equipped with lane-departure prevention devices at the same time. Here we have separated benefits into *benefit derived from system users* and *benefit derived from secondary parties*; for vehicle types not subject to the mandate, we show the *benefit derived from secondary parties*. The amounts of benefits are obtained from losses in 2015.



Note: The amounts of benefits are calculated by multiplying losses in 2015 by the average vehicle life expectancy.

Figure 1: Marginal benefit curves and optimal market diffusion rate for lane-departure prevention technologies (passenger vehicles)



Note 1: Type 1: standard/small buses, Type 2: standard/small passenger vehicle for private use, Type 3: standard/small passenger vehicle for commercial use (taxi), Type 4: mini vehicle, Type 5: standard/small truck at over 3.5 ton GVW, Type 6: standard/small truck at 3.5 ton or less GVW.

Note 2: Mini vehicles include mini trucks and mini passenger vehicles.
Note 3: The amounts of benefits are calculated by multiplying losses in 2015 by the average vehicle life expectancy.

Figure 2: Impact per vehicle of mandatory installation regulations

7. Discussion and conclusions

In this study, we first used data from the J-TAD (macro) to compute the frequency of lane-departure accidents and the damages resulting from these accidents, then estimated several quantities of economic interest: the marginal benefit of lane-departure prevention devices, the optimal market-diffusion rate for these devices, the fraction of their total social benefit accounted for by the *benefit derived from secondary parties*, and the impact of regulatory policies to mandate the installation of these devices. In this final section, we consider the implications of our findings for policy decisions.

First, at market diffusion rates of 11.0 %, 33.3%, and 64.2%, the *benefit derived from secondary parties* account respectively for 21.9 %, 23.1 %, and 24.1% of the marginal social benefit. Inasmuch as the *benefit derived from system users* include externality benefit other than private benefit to users and this study does not include vehicle-pedestrian accidents, this shows that, for passenger vehicles, achieving optimal market-diffusion rates for lane-departure prevention devices will require purchase economic incentives far exceeding the order of 20 % of the system price (or the imposition of penalties for failing to purchase these devices).

Next, regarding the impact of regulatory policies to mandate the installation of lane-departure prevention devices, these mandates impose a dynamic burden uniformly on all users—irrespective of travel distances or the extent to which users drive safely—and thus it is desirable to employ the economic incentives mentioned above. However, it is difficult to imagine that purchasers will be in possession of all relevant information regarding the frequency of lane departures and the resulting accidents and associated damages. Similarly, the *benefit derived from system users* include benefits enjoyed by fellow passengers in primary parties' vehicles, but purchasers will not always account for benefits to fellow passengers when making purchasing decisions in the marketplace. In view of these observations, one might consider mandatory installation regulations as an alternative policy solution; however, if one adopts this viewpoint, the analytical results of this study lead to the conclusion that all vehicle types should be subject to the mandate if the social cost of producing devices with lane-departure-preventing functionality lies below 10 thousand yen. Alternatively, if one neglects information asymmetries and moral hazards pertaining to fellow passengers' benefits, the presence of external effects—in particular, the fact that vehicles exempt from mandates enjoy large benefits when mandates are imposed upon certain types of vehicles—suggests that such mandates may be justified as a policy alternative to economic incentives. However, in this case—as shown in Figure 2—it is appropriate to assign high priority for mandatory installation to all categories of standard/small trucks.

In future work, we plan to extend this study in three directions: by making our model more rigorous, by expanding the spectrum of benefits we quantify, and by analyzing other accident-prevention technologies.

First, with regard to designing a more rigorous model, in the present study we assumed that the installation of lane-departure-prevention devices is 100% effective in avoiding lane-departure accidents, but this is unrealistic. Future work will require refining the parameters in our model by making use of resources such as analytical results from simulations of traffic accidents in autonomous driving systems conducted by the Strategic Innovation Program (SIP) in Japan. Also, the values we used in this work for monetary and non-monetary losses per a victim in each of the various bodily-injury severity classes were independent of the type of accident. However, it is easy to imagine that losses may differ significantly for different types of accidents; for example, the fraction of all monetary losses accounted for by material losses is surely not the same for vehicle-vehicle accidents and single-vehicle accidents, and within the category of single-vehicle accidents this fraction surely differs for accidents on general-purpose roads and on highways. Accounting for these distinctions will require a more fine-grained analysis of base units for loss amounts for each of the various types of accidents. In addition, results in this paper are based only on data for the year 2015. Expansion of periods for analysis is needed for obtaining more robust results.

Next, with regard to enlarging the scope of the benefits we quantify, this study does not include vehicle-pedestrian accidents. In order to calculate the benefits from reduction of vehicle-pedestrian accidents, classification in Cabinet Office (2015) has to be elaborated. In addition, the base units for non-monetary losses used in this study include only the pain and suffering experienced by the victims of traffic accidents themselves, and do not include pain and suffering on account of the family members of victims. Thus, the benefit estimates in this study are most likely underestimates *quoad hoc*. Moreover, in this study we have entirely neglected important benefits enjoyed by users of technology system devices, including the benefit of a more pleasant driving experience. Collecting numerical data on this sort of benefit will require surveying users of accident-prevention systems to gauge willingness to spend money for such benefits.

Finally, with regard to analyzing other accident-avoidance technologies, we hope to expand our analysis to consider systems for avoiding rear-end accidents, right-turn accidents, accidents involving collisions in intersections, and other types of accidents. The lane-departure prevention technologies that are the focus of this paper are autonomous technologies that gather information on a vehicle's driving environment solely through the use of cameras and sensors mounted on the vehicle. However, systems for avoiding other types of accidents include not only autonomous technologies but also cooperative technologies that gather information on driving environment via wireless communication with other vehicles or roadside network infrastructure. Because cooperative technologies possess network externalities, the nature of the benefits they offer differs significantly from that of autonomous technologies. Analysis of policies to promote the adoption of these technologies will require the construction of new analytical models distinct from those used to study autonomous systems.

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