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Abstract:

In the years since Google began testing driverless cars on public roads, automated driving systems have been a focus of increasing attention in many nations around the world, with Japan being no exception. In this paper, we consider the economic properties of rear-end collision-prevention technologies – autonomous and vehicle-to-vehicle cooperative technologies- and then formulate and estimate their benefits. Then, we analyze the impact of regulatory policies—specifically, policies that mandate the installation of collision-prevention devices—on the shape of the curve of private benefit. The main conclusions of this paper are as follows. For both autonomous systems and V2Vs, achieving the optimal diffusion rate requires incentives to offset over half the cost of the technologies. Policies to require mandatory installation shift the curve of private benefit to reduce or even eliminate the critical mass.

Keywords: Automated Driving System; Rear-end Collision; Vehicle-to-Vehicle Cooperative Technologies; Autonomous Technologies; Network Externalities; Critical Mass.

JEL codes: C51, C63, D62, R41

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1. Introduction

In the years since Google began testing driverless cars on public roads, automated driving systems have been a focus of increasing attention in many nations around the world, with Japan being no exception. In 2014, the Cabinet Office of Japanese Government set forth a series of goals for the near-future development of automated-driving technology: *to commercialize level-2 semi-automated driving systems—using infrastructure information such as data on traffic signals and traffic jams—by 2017; to target the commercialization of level-3 semi-automated driving systems by the early 2020s; and to strive for the commercialization of level-4 full automated driving systems by the late 2020s.* Automated vehicles have become a topic of keen interest through Japanese society as well, for purposes such as providing means of mobility to senior citizens and other transportation-challenged individuals and eliminating tragic traffic accidents.

Although the technological aspects of automated driving systems have already been addressed by an enormous volume of research, studies in the field of economics—addressing questions such as the benefits of automated vehicles and policies to promote their spread—are only just beginning to emerge. Anderson et al. (2016) offered a comprehensive discussion of the costs and benefits of automated driving systems from the perspectives of safety and crashes, mobility for those unable to drive, energy and emissions, land use, and other considerations. The U.S. DOT (2015) classified the impact of automated driving into 7 areas—safety, vehicle and regional mobility, energy and environment, transportation system usage, accessibility, economic benefits, and land use—and discussed methods for measuring and characterizing effects in each category. Analyses in which the effects of automated driving were actually measured include, for example, the work of Anderson et al. (2012), which—like the present paper—focused on the particular case of rear-end collision-prevention devices; their results indicated that, although these technologies contribute significantly to reducing rear-end collisions, their cost-benefit ratio was less than 1 for all but heavy vehicle. In Japan, Yokota and Ueda (1997) studied the Advanced

Cruise-Assist Highway System (AHS) and analyzed costs and benefits for each of the various service levels and types of roads addressed by AHS.

The coming years will surely see a variety of studies conducted from an economic perspective following the analytical framework of the U. S. DOT (2015). However, at present, all of the aforementioned research—including the work of the U.S.DOT (2015)—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. Approaches to designing automated driving systems may be broadly classified into the categories of *autonomous* and *cooperative* systems, with the latter category further subdivided into *vehicle-to-vehicle*, *road-to-vehicle*, *pedestrian-to-vehicle*, and *cloud-based* cooperative systems. Each of these paradigms has its own characteristic features from the standpoint of *externalities*. Research that seeks to develop models for characterizing policies to stimulate market diffusion, and to compare the effectiveness of various such policies, will be important in the years to come.

In this paper, working within the context of the considerations outlined above, we focus on the particular case of rear-end collisions between vehicles. We consider the economic properties of rear-end collision-prevention technologies and estimate their private and external benefits. Then, we analyze the impact of regulatory policies—specifically, policies that mandate the installation of collision-prevention devices—on the shape of the curve of private benefit (that is, the demand curve).

The remainder of this paper is organized as follows. In Section 2, we discuss the types of accidents and prevention technologies we study and the associated benefits we seek to estimate. In Section 3, we discuss our methods for computing benefit and the data we use in our analysis. In Section 4, we discuss the present state of rear-end collisions in Japan, as well as the unique characteristics of these accidents in Japan, using aggregate data on the frequency of traffic accidents and associated casualties obtained via the traffic accident data aggregator maintained by Japan’s Institute for Traffic Accident Research and Data Analysis (ITARDA). In Section 5 we discuss the marginal private and social benefits of collision-prevention technologies and the impact of policies to make them mandatory. Our conclusions are presented in Section 6.

2. The subjects of our analysis

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

2.1. The types of accidents and prevention technologies we consider

In this study we restrict our attention to rear-end collisions, excluding other types of accidents. We consider three technologies that have been developed, or are currently in development, to prevent rear-end collisions: collision mitigating braking systems (CMBSs), adaptive cruise control (ACC), and cooperative adaptive cruise control (CACC). CMBSs use cameras, radar, or other means to detect vehicles or other obstacles in front of a vehicle; the system warns the driver if the risk of collision is present, and—in cases where the system determines that a collision is unavoidable—automatically applies the brakes to mitigate the ensuing damage. ACC systems automatically control the acceleration and braking of a vehicle based on measurements—taken by instruments such as millimeter-wave detectors or cameras—of the distance to the next vehicle on a highway or other road. The distinction between ACC and CMBSs is that ACC systems, unlike CMBSs, automatically control acceleration as well as braking and offer the ability to maintain a fixed distance between vehicles. Finally, in CACC systems, multiple vehicles are interconnected via vehicle-to-vehicle communication links to share information such as acceleration and braking data. In this approach, when a vehicle begins to brake, the vehicle behind it automatically and nearly simultaneously brakes as well. CACC allows more fine-grained maintenance of inter-vehicle distance than is possible with ACC, and may also be applied to convoys of multiple vehicles. According to the classification scheme for automated driving system prepared by the Cabinet Office of Japanese Government (2014), CMBSs are classified as level-1 technologies (systems that automatically control any one of the functions of acceleration, steering, or braking), while ACC and CACC systems are level-2 technologies (systems offering simultaneous control of two or more of these functions). From the system-level design perspective, the ACC and CMBS approaches are both autonomous technologies, in which devices such as cameras or sensors need only be mounted on any one vehicle to make that vehicle aware of its driving environment; in contrast, CACC is a vehicle-to-vehicle cooperative technology (V2V)—indeed, a system for collaboration among vehicles based on inter-vehicle communication—in which information obtained via wireless communication is used to make vehicles aware of their driving environments.

A variety of studies have investigated the extent to which these technologies reduce rear-end collisions and other accidents. Fitch et. al (2008) found that the installation of forward-collision warning (FCW) alarms on heavy vehicles could reduce rear-end collisions by 21%. Anderson et al. (2012) determined that forward-collision avoidance technology (FCAT) systems might reduce fatal crashes and injury crashes by 20-40% and 30-50% respectively. Jeong and Oh (2015) conducted an analysis using a microscopic traffic simulator and concluded that active vehicle-safety systems (AVSS), which include ACC systems, reduce rear-end collisions by 78.8% under certain conditions.

Although the question of the extent to which collision-reduction technologies succeed in preventing accidents has thus been addressed by a variety of prior studies, in the analysis of this paper we assume that all technologies are 100% successful in avoiding rear-end collisions, and we analyze the benefits to users that accrue from the avoidance of accidents. Thus, the only technical consideration that we take into account in analyzing rear-end collision-prevention systems is that for whether these systems are autonomous or cooperative; the actual collision-avoidance performance of the various technologies lies outside the scope of this paper. Our reasons for adopting this analytical approach are twofold: 1) the variety of disparate measurement results make it difficult to identify unique parameter values quantifying the accident-reduction performance of various technologies, and 2) by placing questions of performance outside the scope of our considerations, we obtain a clearer separation between autonomous and cooperative technological approaches and the private benefits delivered to users by each approach. On the other hand, our assumption that all technologies are 100% effective in avoiding collisions has the consequence that the analytical results of this study do not amount to a characterization of the benefits derived from actual technologies.

2.2. The benefits we calculate

As noted briefly above, the benefits we seek to quantify are those derived from the avoidance of traffic accidents and the associated losses. The ACC and CACC systems discussed above actually offer additional benefits beyond the prevention of accidents: they assist users in executing routine driving operations, reducing bodily fatigue on the part of drivers. However, this type of benefit lies outside the range of our analysis in this paper. Like our unrealistic assumption regarding the performance of accident-prevention technologies, this restriction on the scope of our analysis is a significant additional limitation ensuring that the benefits computed in this research differ from the actual benefits that would be derived from the technology in practice.

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 (medical expenses, lost wages due to missed work, etc.), material losses (such as 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 (such as emergency transportation costs and costs of accident handling by police). On the other hand, non-monetary losses include the following: 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; and the psychological burden on the persons responsible for causing the accident and their families and friends. Among these various types of damage, the Cabinet Office of Japanese Government (2012) determines the amounts of non-monetary losses based on the pain and suffering experienced by the actual victims of accidents themselves, treating deaths and injuries as separate categories.

Based on this separation of monetary and non-monetary losses, in this study we consider the avoidance of *non-monetary losses* to be the benefit derived from the purchase of accident-prevention devices. The reason for this is that a significant portion of monetary losses are covered by liability insurance, whereupon we expect that the motivation for consumers to purchase rear-end-collision prevention technologies will be to avoid non-monetary losses.

3. Methods for computing benefits

Based on the analytical framework outlined above, the computational methodology and data we use to compute private benefits are as follows.

3.1. Computational methods

Based on the fundamental assumption that a user's probability of experiencing an accident—and thus the benefit derived from installing an accident-prevention device—increases as the user's travel distance increases, we use the following method to compute private benefit.

First considering autonomous systems, a characteristic feature of the economics of these systems is that they prevent the user's vehicle from suffering rear-end collisions irrespective of whether or not the vehicle in front is equipped with the technology. Thus the private benefit $U^a_{i,k}$ derived by individual *i* from the use of vehicle type *k* equipped with an autonomous accident-prevention system may be defined as:

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

Here $d_{i,k}$ is the annual distance traveled by individual *i* using vehicle type *k,* which we assume to be described by a certain probability distribution. n_l is the number of automobiles (number of users) for vehicle type *l*. $a_{k,l}$ is defined by $a_{k,l} = A_{k,l} / (d_k * d_l)$, where $A_{k,l}$ is the annual number of rear-end collisions involving a vehicle of type *k* in the rear and a vehicle of type *l* in the front, while d_k, d_l are the annual travel distances (in vehicles × kilometers) traveled by vehicles of types *k* and *l*. $v_{k,l}$ denotes the non-monetary losses per accident for the rear vehicle in a rear-end collision involving a vehicle of type *k* in the rear and a vehicle of type *l* in the front. *m* is the number of vehicle types; in this study we consider 6 types of vehicles: standard-size and small cargo vehicles, light cargo vehicles, standard-size and small buses, standard-size and small passenger vehicles for commercial use (taxies), standard-size and small passenger vehicles for private use, and light passenger vehicles. t_k is the number of years of use for vehicle type *k*, and *r* is the discount rate for which we use the value of 0.04.

If use of a technology spreads, vehicles in which it is installed derive additional benefit from the avoidance of collisions with vehicles behind then that are also equipped with the technology. This effect is not included in the equation above. Indeed, this benefit is enjoyed by drivers of *all* vehicles, whether or not they are equipped with the technology, and thus it is not a private benefit derived upon purchase of the device. The magnitude of this externality benefit derived when individual *i,* using vehicle type *k* installs an autonomous system may be expressed as follows:

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

Here $w_{k,l}$ denotes the non-monetary losses per accident for the front vehicle in a rear-end collision involving a vehicle of type *k* in the rear and a vehicle of type *l* in the front.

Turning next toV2Vs, the characteristic economic feature of these systems is that they are only able to prevent rear-end collisions in cases where both the front and rear vehicles are equipped with the technology. From the perspective of the driver of the rear vehicle, collisions with the front vehicle are avoided only if both his or her own vehicle has the technology *and* the front vehicle has the technology. From the perspective of the driver of the front vehicle, collisions with the rear vehicle are avoided only if both his or her own vehicle has the technology *and* the rear vehicle has the technology. Thus the private benefit$U_{i,k}^{c}$ enjoyed by individual *i* from the use of vehicle type *k* equipped with a V2V may be defined as follows:

$$U_{i,k}^{c} = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t}(d_{i,k} * (\sum_{l=1}^{m}(\sum_{j=1}^{q_l} d_{j,l} * a_{k,l} * v_{k,l} + \sum_{j=1}^{q_l} d_{j,l} * a_{l,k} * w_{l,k})). \qquad (3)$$

Here q_l denotes the ranking, in descending order of travel distance, of the marginal user with the shortest travel distance among all vehicles of type *l* equipped with the technology. Thus the quantity $\sum_{j=1}^{q_l} d_{j,l}$ is the annual travel distance (in vehicles × kilometers) of vehicles of type *l* that are equipped with the technology.

In this study we have computed private benefits for just two types of passenger vehicles: standard/small vehicles for private use and light vehicles (Japanese “K-car”); we have not performed calculations for other four types of vehicles. The reason is that cargo vehicles, buses and passenger vehicles for commercial use are frequently the property of corporations, to which we believe the notion of private benefits derived from avoiding non-monetary losses is not applicable. However, we do estimate the magnitude of the non-monetary losses for passengers in these types of vehicles that would result if the installation of V2V devices were made mandatory for such vehicles.

3.2. The data we use

We next discuss the data values we used for the various variables in the equations above. Our data values are Japanese and taken from roughly the year 2012.

3.2.1. Number of automobiles and annual travel distance

First, to determine the numbers of vehicles of various types owned in 2012, we obtain data from the website of Japan’s Automobile Inspection & Registration Information Association for the numbers of vehicles of various types owned at the end of fiscal year 2011 and at the end of fiscal year 2012, then take the average of these numbers as the number of vehicles of each type owned in mid-year 2012.

Next, assuming that travel distances for passenger vehicles will be distributed according to a log-normal distribution, we use monthly travel-distance data from the Japan Automobile Manufacturers Association (2013) to determine the average and median monthly travel distances, then use these to compute the parameters in the log-normal distribution of annual travel distances. The average annual travel distances obtained in this way disagree with the average annual travel distances that may be computed from the numbers of vehicles owned by type (described above) and total travel distance by vehicle type in the *Monthly Report of Automobile Transport Statistics* from Japan’s Ministry of Land, Infrastructure, Transport and Tourism; we correct the parameters in the log-normal distribution to ensure agreement.

To compute the private benefit for a passenger vehicle requires knowledge of annual travel distances for other vehicle types; to compute these, we assume that travel distances are identical for all vehicles of a given type and use the average value of the annual travel distance for each vehicle type that may be computed from the *Monthly Report of Automobile Transport Statistics* and the number of vehicles owned.

3.2.2. Numbers of traffic accidents and casualties

To aggregate numbers of traffic accidents and casualties, we used the traffic accident data aggregator provided by ITARDA. These data cover only accidents involving fatalities or bodily injuries; they do not include accidents in which property is damaged but no personal injuries result.

3.2.3 Base units for non-monetary losses

Table 1 lists the non-monetary losses for personal injuries of various degrees of severity. The value listed here for losses in case of death is the 2009 value established by the Cabinet Office of Japanese Government (2012) in 2012 yen (inflation-adjusted by GDP-deflator). Next, for losses in case of injury, we note that the Cabinet Office (2012) categorizes injuries into 8 sectors (Q, W, E, R, Y, I, O, and A) based on "patient status at hospitalization (degree of injury)" and "patient status after discharge from hospital (after effects)" and estimates loss values for each sector. In contrast, personal-injury data from ITARDA's Traffic accident data are classified[1] into just three severity classes—death, serious injury, and slight injury—a categorization that differs from that of the Cabinet Office (2012). Here we have assumed that the ITARDA category of "slight injury" corresponds to injury sector A in the Cabinet Office classification scheme, while the other 7 categories in the Cabinet Office scheme correspond to ITARDA's "serious injury," and we have used this assumption to set non-monetary losses for slightly and serious injuries[2]. In calculating the non-monetary loss for "serious injury," we considered the composition of 7 categories in 2012 using data obtained from the General Insurance Rating Organization of Japan (2013). The results listed in Table 1 are also in 2012 yen. In the following calculations, however, we do not use these non-monetary values in yen but do index numbers expressed with the non-monetary loss for "death" set to 10,000. This accounts for the fact that non-monetary losses in Table 1 are the financial equivalents of the pain and suffering experienced only by the victim of a traffic accident himself

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[1] In the *Statistical Data on Traffic Accidents* prepared by Japan's National Police Agency, "deaths" are cases in which a traffic accident results in death within 24 hours of the accident. "Serious injuries" are injuries requiring medical treatment for 1 month (30 days) or more. "Slight injuries" are injuries requiring medical treatment for less than 30 days.

[2] In the classification scheme of the Cabinet Office of Japanese Government (2012), the difference between injury classes O and A is the presence or absence of residual disability.

or herself, not including emotional pain and suffering experienced by the friends and family of the victim and by the person responsible for the accident and his or her family and friends.

Table 1: Non-monetary damage amounts for personal bodily injuries of various degrees of severity

Severity of injury	Non-monetary losses (Ten thousand yen)	Index number
Death	20,754	10,000
Serious injury	732	353
Slight injury	23	11

Source: Prepared by author in reference to the Cabinet Office (2012)

3.2.4. Average life expectancy of vehicle

Rear-end collision-prevention devices 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 various types of vehicles.

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 as follows:

$$STOCK_t = SALES_t * \exp(-(\frac{0.5+0}{\eta})^m) + SALES_{t-1} * \exp(-(\frac{0.5+1}{\eta})^m) +$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + SALES_{t-39} * \exp(-(\frac{0.5+39}{\eta})^m) + SALES_{t-40} * \exp(-(\frac{0.5+40}{\eta})^m). \qquad (4)$$

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 have assumed a value of m=3, then determine values of η for each vehicle type by minimizing estimation error of $STOCK_{2012}$. From the values of η thus obtained, we determine the average number of years of use. As inputs to our formula 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. Table 2 lists the results of our calculations.

Table 2: Estimated parameters in the Weibull distribution and average life expectancies of vehicle in 2012

Vehicle type		Weibull distribution		Estimation error	Average number of years of use
		Shape parameter	Scale parameter		
Bus	Standard-size / small	3.0	16.1	0.0	14.4
Passenger	Standard-size / small for commercial use	3.0	14.8	0.0	13.2
	Standard-size / small for pivate use	3.0	14.8	0.0	13.2
	Light (K-car)	3.0	17.3	0.0	15.5
Cargo	Standard-size / small	3.0	14.0	0.0	12.5
	Light (K-car)	3.0	17.8	0.0	15.9

Note: 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.

4. Rear-end collisions: How they arise and how they are unique

Before presenting the results of our calculations of private benefit, we first present results from traffic accident data aggregator provided by ITARDA for numbers of traffic accidents and traffic-accident casualties in Japan.

4.1. Characteristic features of losses resulting from traffic accidents

Table 3 reports the magnitude of non-monetary losses of various types of traffic accidents between four-wheel vehicles in the year 2012 in Japan. According to this method of accounting, rear-end collisions are the most damaging of the 6 types of accidents considered, contributing 5,040,468 or approximately one-third, to the total weighted sum.

Table 3: Non-monetary losses for various types of accidents between four-wheel vehicles in the year 2012 in Japan

Type of accident	Primary party	Fellow passengers in primary party's vehicle	Secondary party	Fellow passengers in secondary party's vehicle	Total
Frontal	2,636,875	795,828	959,323	367,074	4,759,101
Rear-end	706,254	223,264	2,998,420	1,112,530	5,040,468
Right-angle	1,095,308	548,401	1,529,191	592,262	3,765,162
Right-turn	317,254	241,227	515,629	162,225	1,236,335
Left-turn	16,897	13,176	33,001	10,706	73,781
Other	0	106,346	605,147	0	711,492
Total	4,772,588	1,928,243	6,640,711	2,244,797	15,586,340

Note: The number reported for each category is computed by the following formula: 10,000*(number of accidents resulting in death) + 353*(number of accidents resulting in serious injury) + 11*(number of accidents resulting in minor injury). Numbers of accidents of each type and severity class are obtained using ITARDA’s traffic accident data aggregator.

One characteristic feature of rear-end collisions concerns the relative amounts of losses for the primary and secondary parties. Here the *primary* party in a traffic accident is the party (driver) judged to be more at fault for the accident; if both parties are equally at fault, the primary is the party whose bodily injuries are less severe. The *secondary* party is the party judged to be less at fault, or (if both parties are equally at fault) the party whose bodily injuries are more severe. In rear-end collisions, losses for secondary parties, or for fellow passengers in the secondary-party vehicle, are relatively large compared to those arising in other types of accidents. In the majority of rear-end collisions, the driver of the rear vehicle is the primary party and the driver of the front vehicle is the secondary party; this has the consequence that, in rear-end collisions, the extent of the bodily injury suffered by the occupants of the vehicle in front is typically greater than that for the vehicle at rear.

4.2. Numbers of accidents

Table 4 lists numbers of rear-end collisions in the year 2012 in Japan, presented in the form of a matrix indexed by the type of vehicle in front and the type of vehicle at rear. The ITARDA's traffic accident data aggregator does not allow numbers of accidents or casualties to be classified according to the type of front or rear vehicle. Thus, for cases in which the collision affected the front of the secondary party's vehicle, we assume that the secondary party's vehicle was the rear of the two vehicles[3]; the data of Table 4 are prepared using aggregate statistics for this case and correcting the aggregate values in the primary-vehicle-type/secondary-vehicle-type matrix of values obtained from ITARDA.

Based on this analysis, we identify 218,548 rear-end collisions between the types of vehicles we consider in 2012, of which 108,908, or approximately one half, standard-size or small passenger vehicles used for private purposes were the rear vehicle. Adding to this the number of accidents in which standard-size or small passenger vehicles for commercial use or light passenger vehicles

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[3] For collisions between a rear four-wheel vehicle and a front four-wheel vehicle that occur when the front vehicle changes directions while the rear vehicle proceeds in a straight line, the basic delinquent ratio is 70% for the front vehicle and 30% for the rear vehicle in Japan. Thus, in this case the front vehicle is the primary and the rear vehicle is the secondary.

were the rear vehicle, we find that passenger vehicles are the rear vehicle in just under 80% of rear-end collisions.

However, needless to say, these results are heavily influenced by the numbers of vehicles and travel distances for various types of vehicles. For this reason, we normalize the numbers of accidents in Table 4 by dividing by the product of the annual travel distances of the front and rear vehicles (in units of 1 billion km) and use them as values of a_{il} in Eqs. (1), (2) and (3).

Table 4: Numbers of rear-end collisions by vehicle type in 2012

Rear vehicle / Front vehicle		Bus	Passenger			Cargo		Total
		Standard-size / small	Standard-size / small for private use	Standard-size / small for commercial use	Light (K-car)	Standard-size / small	Light (K-car)	
Bus	Standard-size / small	10	182	12	103	61	21	389
Passenger	Standard-size / small for private use	238	57,439	1,629	29,940	13,731	7,985	110,962
	Standard-size / small for commercial use	24	2,741	833	1,020	635	366	5,619
	Light (K-car)	94	32,197	654	21,205	6,737	5,307	66,194
Cargo	Standard-size / small	66	7,644	274	3,482	4,579	1,366	17,411
	Light (K-car)	39	8,705	196	4,820	2,563	1,650	17,973
Total		471	108,908	3,598	60,570	28,306	16,695	218,548

4.3. *Severity of personal bodily injuries*

Table 5 reports, in the form of a matrix indexed by the types of the front and rear vehicles, the non-monetary losses per rear-end collision incurred by riders (driver and fellow passengers) in the rear vehicle (v_{kl} in Eqs/ (1) and (3)). Table 6 reports is similar, but reports non-monetary losses per rear-end collision incurred by riders in the front vehicle (w_{kl} in Eqs. (2) and (3)). From Table 5 we see that, irrespective of the type of the rear vehicle, the rear vehicle experiences greater losses when the front vehicle is a standard or small cargo vehicle or a standard or small bus. We attribute this to the fact that this category includes cases in which the front vehicle is a large vehicle with relatively greater distance from the ground to the vehicle chassis; in such cases, rear-end collisions may result in the primary party's vehicle sliding underneath the chassis of the front vehicle, causing significant damage. Next, from Table 6 we see that non-monetary losses incurred by front vehicles are greater than those incurred by rear vehicles. As noted above, this is a characteristic feature of rear-end collisions. We see also that losses for the front vehicle tend to be greater in cases where the rear vehicle is a standard or small cargo vehicle or a standard or small bus.

5. Calculation of benefits and the impact of mandatory installation

We now compute the benefits derived from rear-end collision-prevention systems and enjoyed by two types of passenger vehicles for both autonomous systems and V2Vs. For V2Vs, we further consider the ways in which user benefits would be affected by policies to strengthen legislative safety regulations for road transport vehicles by requiring mandatory installation of collision-prevention devices.

Table 5: Non-monetary losses per collision for riders in the rear vehicle in 2012 ($v_{k,l}$ in Eqs. (1) and (3))

Front vehicle	Rear vehicle	Bus	Passenger			Cargo		Average over all vehicle types
		Standard-size / small	Standard-size / small for private use	Standard-size / small for commercial use	Light (K-car)	Standard-size / small	Light (K-car)	
Bus	Standard-size / small	58.6	181.7	8.3	23.8	32.2	27.4	99.6
Passenger	Standard-size / small for private use	3.6	5.9	4.3	6.7	15.0	9.2	7.5
	Standard-size / small for commercial use	3.2	4.3	3.1	3.6	21.2	4.7	5.9
	Light (K-car)	3.0	4.5	5.3	4.2	10.5	9.6	5.4
Cargo	Standard-size / small	7.5	13.1	5.5	11.6	73.6	53.0	31.7
	Light (K-car)	1.4	4.1	1.8	2.8	7.0	3.9	4.1
Average over all vehicle types		5.0	6.1	4.2	5.8	22.9	12.3	8.6

Note: Values in this table are computed using the same formula used for Table 3.

Table 6: Non-monetary losses per collision for riders in the front vehicle in 2012 ($w_{k,l}$ in Eqs. (2) and (3))

Front vehicle	Rear vehicle	Bus	Passenger			Cargo		Average over all vehicle types
		Standard-size / small	Standard-size / small for private use	Standard-size / small for commercial use	Light (K-car)	Standard-size / small	Light (K-car)	
Bus	Standard-size / small	48.6	17.0	9.3	14.1	13.1	5.3	15.5
Passenger	Standard-size / small for private use	11.3	12.7	13.2	13.1	19.7	11.2	13.6
	Standard-size / small for commercial	11.1	11.0	11.8	11.8	10.9	10.8	11.2
	Light (K-car)	11.1	12.5	12.4	11.9	25.3	11.7	13.5
Cargo	Standard-size / small	68.6	16.6	12.5	18.1	38.4	12.2	22.4
	Light (K-car)	10.3	15.0	11.5	12.8	30.9	12.6	16.4
Average over all vehicle types		20.0	13.1	12.6	12.9	24.9	11.6	14.4

Note: Values in this table are computed using the same formula used for Table 3.

5.1. Results of benefit calculations

Figure 1 shows the marginal private benefit and marginal social benefit for autonomous systems and V2Vs. For autonomous systems, the marginal social benefit is the sum of the marginal private benefit derived by a marginal user installing the device (Eq. (1)) and the externality benefit derived by other drivers enjoying fewer rear-end collisions when driving in front of vehicles equipped with the devices (Eq. (2)). On the other hand, the marginal social benefit for V2Vs is the sum of the marginal private benefit derived by a marginal user installing the device (Eq. (3)) and the network externality benefit enjoyed by users who have already installed the devices themselves due to the reduced rate of rear-end collisions resulting from communication with the marginal user. From these curves we see that the curves of marginal private benefit and marginal social benefit deviate significantly for both autonomous systems and V2Vs, indicating that incentives to assist in purchasing these systems (or penalties for failing to purchase them) will be required to achieve optimal market diffusion. Because losses in rear-end collisions are more severe for the front vehicle than for the rear vehicle, for autonomous systems there are marginal external effects that exceed marginal private benefits. For V2Vs, we see marginal externalities that slightly exceed marginal private benefits. This is because the distances traveled by early adopters are greater than the distances traveled by the marginal user. The fact that marginal externality effects are greater than marginal private benefits for both autonomous and cooperative systems means that governments will need to provide incentives to offset more than half the cost of the systems in order to achieve optimal market diffusion of the technologies.

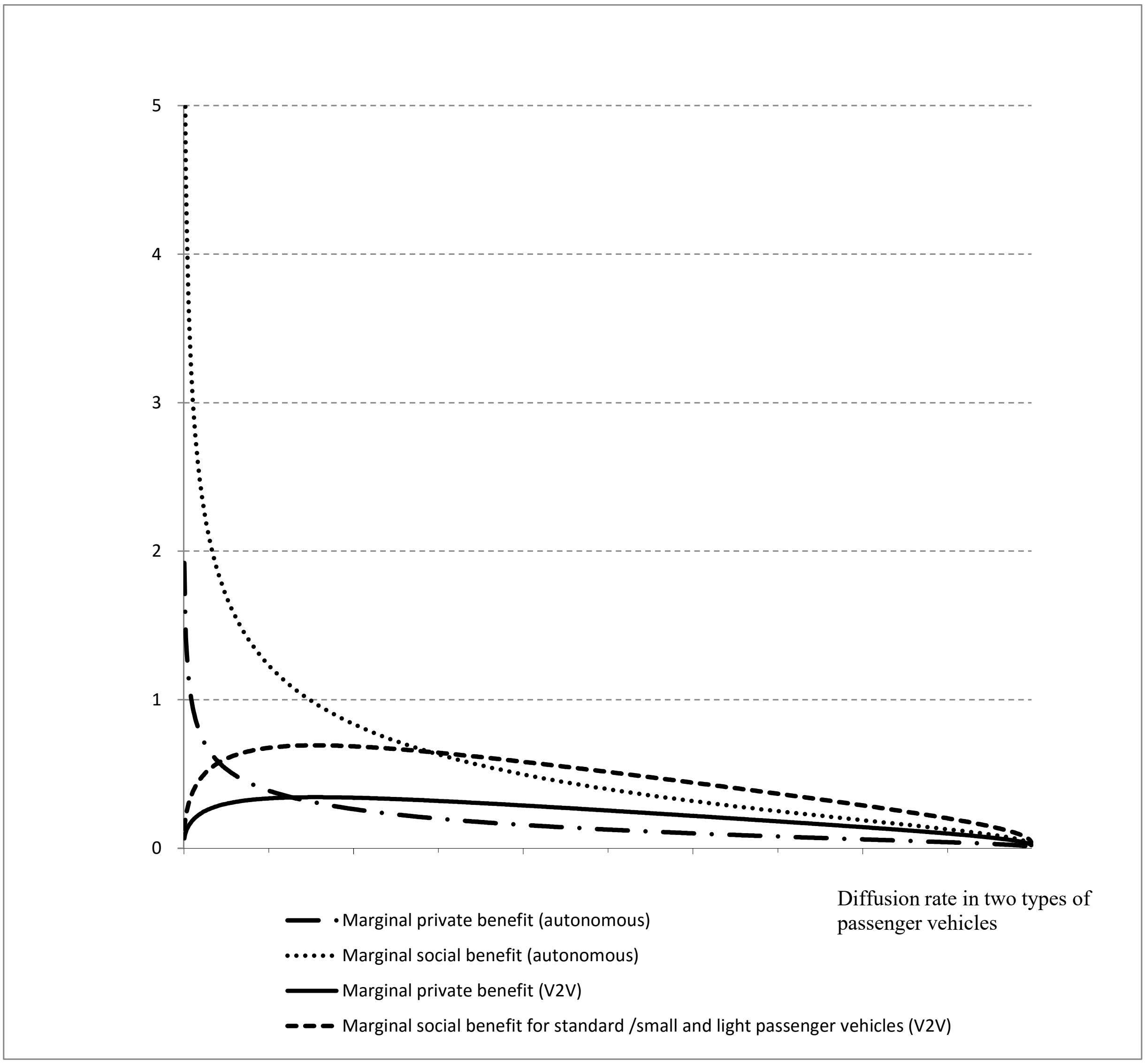

Figure 1: Curves of marginal private benefit and marginal social benefit

Figure 2 plots the decrease in non-monetary losses for rear-end collisions due to increasing diffusion rates for collision-prevention technologies; the vertical axis is normalized so that the value 1 corresponds to the sum of all non-monetary losses[4]. We see that, for identical diffusion rates, the impact of V2Vs is less than that of autonomous systems. This is because V2Vs are only effective when installed in both vehicles, whereupon the impact of these systems is slower to emerge.

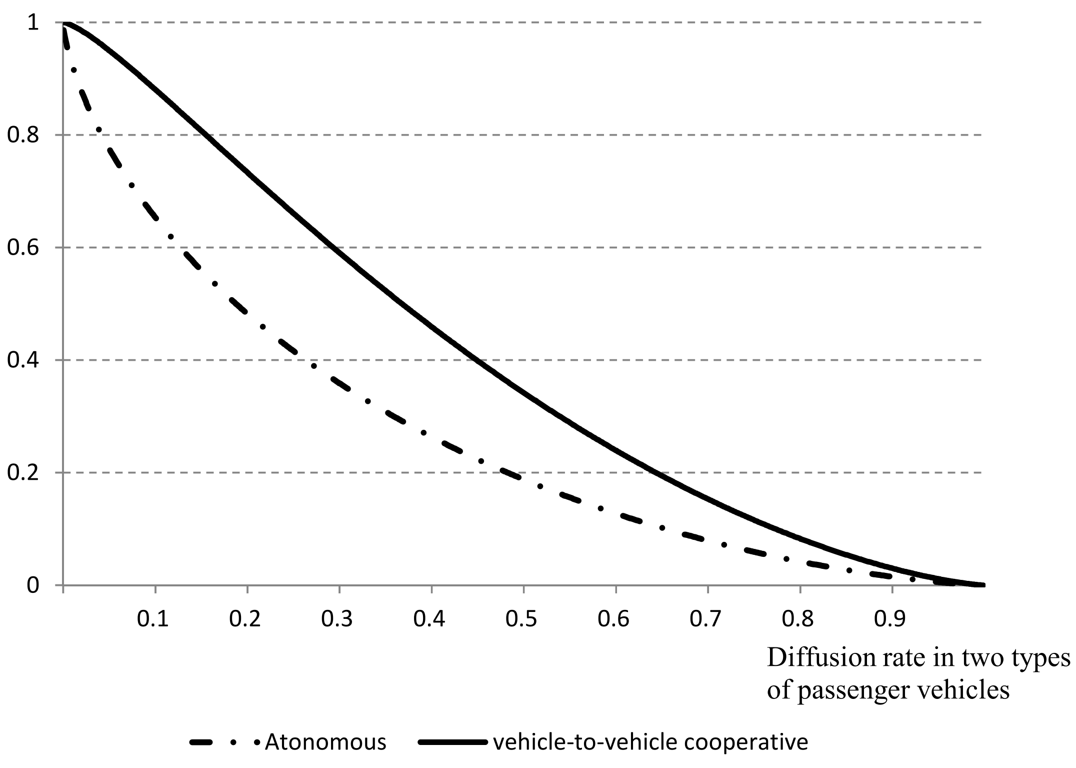

Figure 2: The relationship between non-monetary losses and diffusion rate

5.2. The impact of mandatory installation policies

With regard to safety regulations concerning automated driving, in Japan the installation of collision-mitigating brakes was made mandatory for large buses and trucks and has been

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[4] The amount of benefit from the autonomous technologies at 100% diffusion rate is greater than that of V2Vs because the former includes externality benefit enjoyed by four types of vehicle other than two types of passenger vehicles while the latter does not.

required for new vehicles since 2014. In addition, for buses and trucks with gross weights of 3.5 tons or more, the installation of lane departure warning systems (LDWSs) was made mandatory beginning in 2017. How are the benefits of such systems affected by strengthening safety standards to mandate their installation? In this section we consider this question for the case of V2Vs.

Figure 3 shows how the marginal private benefit derived by passenger-vehicle users changes under three scenarios: *Case* 1: V2Vs are installed by all standard-size and small passenger vehicles for commercial use (taxes) and by all standard-size and small buses for commercial and private use, *Case* 2: V2Vs are installed by 20% of standard-size and small cargo vehicles for private and commercial use, *Case* 3: V2Vs are installed by 50% of standard-size and small cargo vehicles for private and commercial use. In this figure, the curve labeled "Base case" is the marginal private benefit for passenger cars assuming that all vehicle types other than passenger cars are *not* equipped with the technology. This is the same marginal private benefit curve shown in Figure 1 for the case of V2Vs.

From Figure 3 we see that mandatory installation shifts the curves of marginal private benefit upward, with the magnitude of the shift increasing in the order Case 1—Case 2—Case 3. Curves of marginal private benefit for products or services that possess network externalities exhibit the inverted-U shape apparent for the base-case curve (Rohlfs, 1974). Thus, assuming the cost of the device to be 0.25, Base case has two equilibrium points at diffusion rates of f_1 and f_2. The point f_1 is known as the *critical mass*; once the market diffusion of the devices has exceeded this threshold, their diffusion continues, proceeding toward point f_2. Needless to say, mandating device installation for other types of vehicles reduces this threshold value. For Cases 2 and 3, the threshold itself ceases to exist, thus exhibiting a large impact on the spread of the devices among the passenger-vehicle fleet.

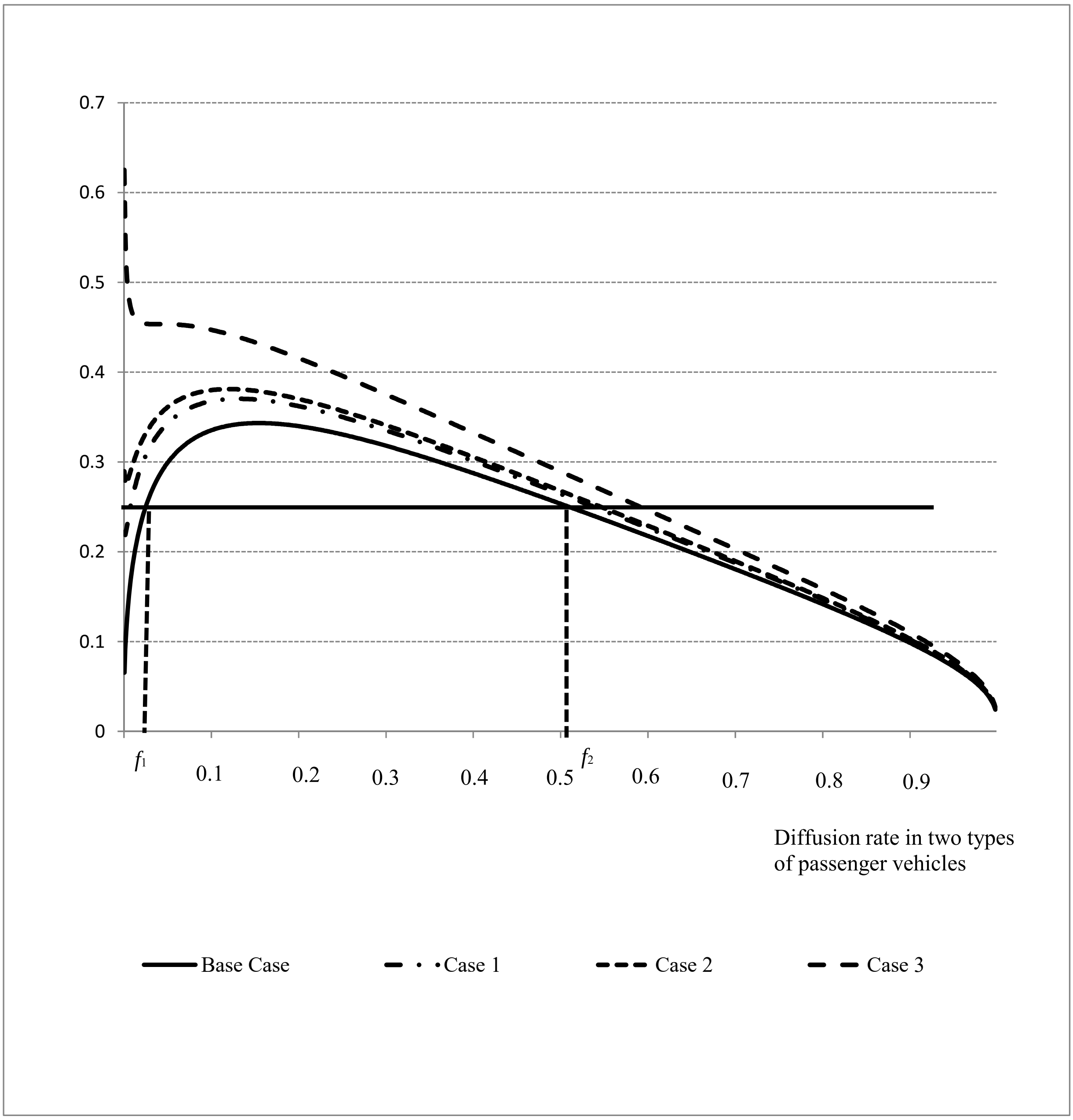

Figure 3: Variation in marginal private benefit resulting from mandatory installation of V2V devices

Meanwhile, what benefits do mandatory-installation policies yield for the parties subject to the mandate? Figure 4 shows the average benefit derived from avoidance of traffic accidents and the associated losses enjoyed by each individual vehicle subject to the mandate. In this figure, the curve labeled e.g. “standard-size / small passenger vehicles for commercial use” and “standard-size / small buses” shows the average benefit per vehicle derived by vehicles in Case 1 above. Note that, in Figure 4, the benefit derived by standard-size and small passenger vehicles for commercial use is greater than that for other vehicle types. This is due to the relatively large numbers of rear-end collisions experienced by a standard-size and small passenger vehicles for commercial use.

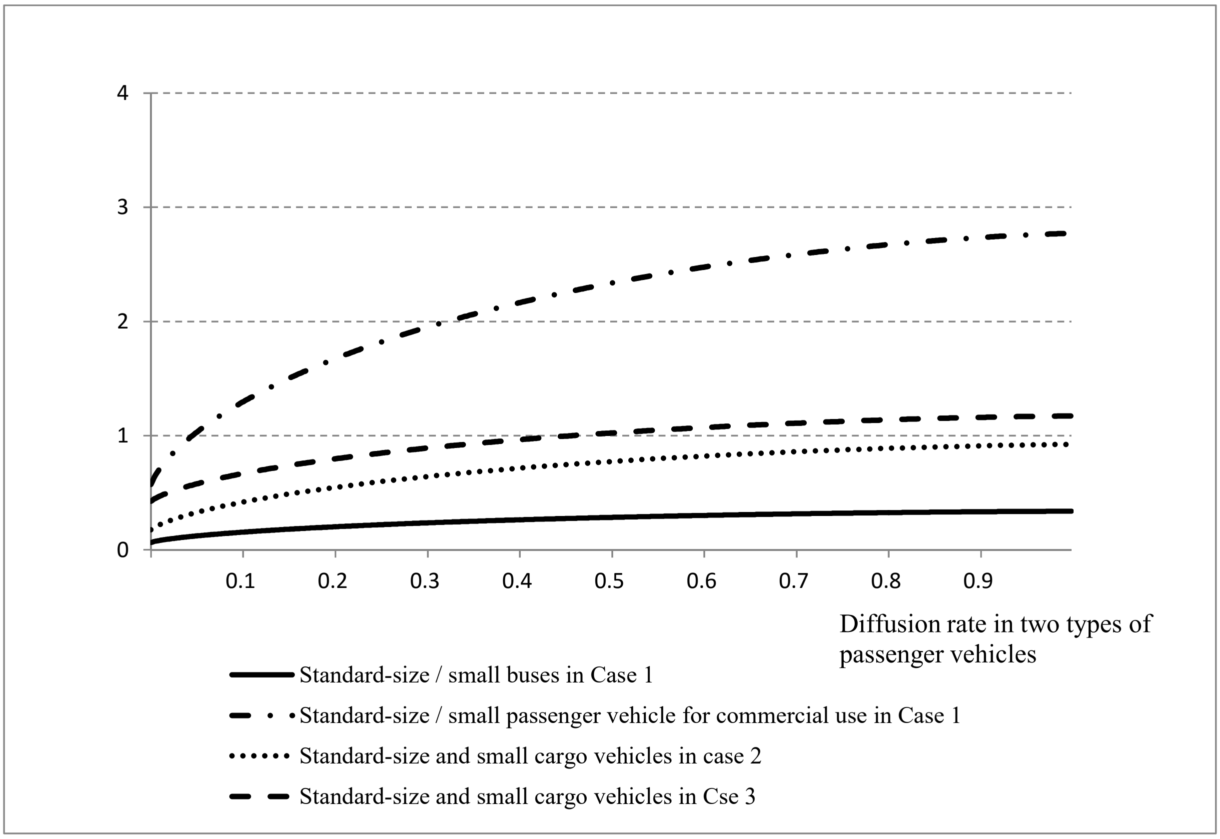

Figure 4: Average benefit derived by an individual vehicle subject to mandatory V2V device installation

6. Conclusion and further research

In this paper we computed the benefits of autonomous systems and V2Vs for avoiding traffic accidents, focusing specifically on the case of rear-end collisions and using a model that accounts for the characteristic economic features of the two types of systems. Then we assessed the impact of policies to require mandatory installation of V2Vs. Our results include the following findings. 1) For both autonomous systems and V2Vs, achieving the optimal diffusion rate requires incentives to offset over half the cost of the technologies. 2) Policies to require mandatory installation shift the curve of private benefit to reduce or even eliminate the critical mass.

In future work, we will expand on this study in three ways: 1) by making our model more rigorous, 2) by broadening the range of benefits we compute, and 3) by analyzing other types of accidents. First, regarding the rigor of the model, in this study we assumed that rear-end collision-prevention devices are 100% effective in avoiding rear-end collisions, a hypothesis that is clearly unrealistic. Improving this aspect of our model will require introducing more fine-grained parameters based on inputs such as the results of traffic-accident simulations performed by SIP (Japanese Cross-ministerial Strategic Innovation Promotion Program). Next, in broadening the type of benefits we compute, it is important to consider key benefits other than the non-monetary benefits we considered in this research—for example, benefits associated with a more pleasant driving experience. The magnitude of the benefits offered by various devices cannot be discussed without including this type of benefit. To incorporate such benefits will require the use of surveys to assess the amounts that consumers are willing to pay for traffic-prevention devices. Finally, in analyzing other types of accidents we must consider right-turn collisions, right-angle collisions, and other types of inter-vehicle accidents. Although in this research we considered only two types of technologies—autonomous systems and V2Vs—for right-turn and right-angle collisions it is also possible to design road-to-vehicle systems for preventing accidents. It is important to expand our benefit-computation model to account for the economic features of such systems and compare the nature and magnitude of the benefit derived from all three types—autonomous, vehicle-to-vehicle, and road-to-vehicle—of accident-prevention technologies.

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