Economic effects of combining technologies in advanced driving assistance systems

Hiroaki Miyoshi

ITEC Working Paper Series

17-03

November 2017

AP-SP1206

Economic effects of combining technologies in advanced driving assistance systems

Hiroaki Miyoshi[1*]
1 Doshisha University, Japan
[*] Kyoto, Japan 602-8580; Tel: 81-75-251-3837; hmiyoshi@mail.doshisha.ac.jp

Abstract
In this study, we analyze the economic benefits from using advanced driving assistance systems. Specifically, we focus on how these benefits change when standalone and vehicle-to-vehicle systems—two quite distinct technologies—are combined. The main, novel insights are two. First, the combination significantly facilitates solving the critical-mass problem for vehicle-to-vehicle systems. Second, rather than a strict separation of coverage regions, it may be more advantageous for standalone and vehicle-to-vehicle systems to have some overlap in the types of accidents they prevent.

KEYWORDS:
Advanced driving assistance systems, Standalone system, Vehicle-to-vehicle systems

1. Introduction
Advanced driving assistance systems (ADAS) can be broadly divided into two categories. One is standalone systems, in which the information needed to enable collision avoidance is obtained from on-board sensors mounted on the vehicle. These systems include lane departure warning systems and automatic emergency braking systems. The other is cooperative systems, in which the information is gathered via communication with other vehicles (V2Vs) or through a network infrastructure, including roadside equipment (V2Is). Some studies evaluate the effects of combinations of different categories of systems from the technological perspective (e.g., Jia and Ngoduy, 2016; Shin and Prevedouros, 2016; Vegni and Little, 2011). However, a small number of studies investigate the economic effects of such combinations (e.g. Kii and Miyoshi, 2011; Li and Kockelman, 2016). In this study, we analyze the economic benefits from ADAS use, with a focus on how the shapes of marginal-benefit curves change when standalone and vehicle-to-vehicle systems are combined. This perspective makes our research very unique when compared to previous studies and contribute much to investigate policy prescriptions for ensuring the diffusion of ADAS in the market.

The remainder of this paper is organized as follows. In Section 2, we discuss the types of accidents and accident-prevention systems we study and the major assumptions in this study. In Section 3, we present the computational methods and data sources we use for benefit computations. In Section 4, we investigate the ways in which the shapes of marginal-benefit curves for accident-prevention system devices are affected by the combination of standalone and vehicle-to-vehicle systems. Finally, we discuss policies for promoting market diffusion of ADAS in Section 5.

2. Types of accidents, prevention technologies, and major assumptions
We focus on vehicle-vehicle collision prevention technologies and their benefits. From an accident-prevention perspective, standalone systems, V2Vs, and V2Is do not offer the same opportunities. For example, it is very difficult for standalone systems to prevent right-angle collisions at intersections and right-turn undercut collisions, while the other two systems might be useful in this regard. V2Is can help prevent collisions during merging, while V2Vs cannot.

Nonetheless, to simplify the analysis, we restrict our scope and make assumptions as follows. The following assumptions include strong ones. We believe, however, that the essence of the following discussion will remain almost same even if we relax the assumptions.

First, we limit our study to standalone systems and V2Vs. Second, for simplicity, we assume that there is no distinction between the types of accidents that may be avoided through standalone systems and V2Vs. Third, we assume that the installation of systems is 100% effective in averting related-accidents. Forth, standalone systems help avoid accidents when the user could be the primary party of an accident. Here, the primary party in a traffic accident denotes the driver (or vehicle) more at fault for the accident, that is,

the person causing the damage. The secondary party, instead, is considered to be less at fault.
Fifth, we assume that the benefits from using standalone systems and/or V2Vs derive from reduction in the losses associated with traffic accidents. According to the Cabinet Office of Japanese Government (2012), losses can be broadly separated into monetary and non-monetary losses. Monetary losses might be personal (e.g., medical expenses and lost wage for missed work), material (e.g., damage to vehicles or structures requiring repairs), incurred by corporate entities (e.g., reduction in added value due to missed work, death, or residual disability), and incurred by public institutions (e.g., emergency transportation costs and costs of accident handling by police). Non-monetary losses include physical or emotional suffering on the part of victims stemming from bodily harm or damage to material property. On the one hand, from the viewpoint of benefits' attribution, the reduction in non-monetary losses is a benefit enjoyed directly by system users. On the other hand, the benefits associated with the avoidance of monetary losses are enjoyed by a variety of economic agents, including corporate entities and public institutions. In this study, we define the benefit derived from system users as the sum of the reduction in monetary and non-monetary losses. Benefit derived from system users differ from private benefits, as the former also include benefits enjoyed by others, like corporate entities and public institutions.

3. Methods for computing benefits

Based on the analytical framework outlined above, we describe the computational methodology and the data we use.

3.1. Computational methods

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

3.1.1 Standalone systems

First, in the case of standalone systems, a characteristic economic feature is that they protect the user's vehicle independently of whether the other vehicle is equipped with the system or not. However, they can avoid accidents only when the vehicle is the primary party.
Thus, the benefit derived from system user (individual *i*) from the use of vehicle of type *k* equipped with a standalone system , $U^a_{i,k}$,may be defined as:

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

Here, $x_{i,k}$ is the annual distance traveled by individual i using a vehicle of type-*k*, which we assume to be described by a certain probability distribution. n_l is the number of vehicles for type-*l*. $a_{k,l}$ is computed by dividing the annual number of accidents in which the primary and secondary parties are respectively of type-*k* and type-*l* by the product of the total annual distance traveled by type-*k* and type-*l*. $v_{k,l}$ denotes losses per accident for the primary party in a collision involving a vehicle of type-*k* as the primary party and a vehicle of type-*l* as the second party. m is the number of vehicle types; in this study, we consider 6 types of vehicles: buses and microbuses, standard-sized passenger cars for private use, standard-sized passenger cars for commercial use (taxis), light passenger cars, large and medium-sized trucks, and standard-sized and light trucks. t_k is the average life expectancy for a vehicle of type-k, and *r* is the discount rate for which we use the value of 0.04.
On the other hand, the benefit derived from the secondary party is enjoyed by all vehicles whether or not they are equipped with the system. The amount of this benefit, $E^a_{i,k}$, derived when individual *i*, using a vehicle of type-*k* installs a standalone system may be expressed as:

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

Here, $w_{k,l}$ denotes losses per accident for the secondary party in a collision involving a vehicle of type-*k* as the primary and a vehicle of type- *l* as the second party.

Next, we introduce equations for the total amount of and the marginal value of social benefit. Hereinafter, we use the benefit derived from system user, U_k^a , and the benefit derived from the secondary party, E_k^a , as a function of x_k (annual distance traveled by a vehicle of type-k), by omitting i from Eq. (1) and (2). The same applies hereafter.
The total amount of the social benefits, $sben^a$ where the diffusion rate of the system is p , may be expressed as:

$$sben^a(p, \mathbf{x}^*) = \sum_{k=1}^{m} sben^a{}_k(p, \mathbf{x}^*) = \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} (U_k^a(x_k) + E_k^a(x_k)) d_k(x_k)\, dx_k,$$

$$\text{where } \mathbf{x}^* = (x_1^*, , x_k^*, , x_m^*), \tag{3}$$

under the condition that vectors (p , $\mathbf{x}^*$) satisfy the following system:

$$F(p, \mathbf{x}^*) = \frac{1}{\bar{n}}\left(\sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} d_k(x_k) dx_k\right) - p = 0, \text{ where } \bar{n} = \sum_{k=1}^{m} n_k, \tag{4}$$

$$U_1^a(x_1)\big|_{x_1^*(p)} = \ldots = U_k^a(x_k)\big|_{x_k^*(p)} = \ldots = U_m^a(x_m)\big|_{x_m^*(p)}. \tag{5}$$

Here, x_k^* is the annual travel distance of marginal system user using a vehicle of type-*k*. d_k denotes the probability density function for vehicle of type-*k* under the assumption that the travel distance for each type of vehicle is lognormally distributed. $U_k^a(x_k)\big|_{x_k^*(p)}$ in Eq. (5) denotes the benefit derived from marginal system user using a vehicle of type-*k*. Eq. (5) means that the benefits derived from marginal system users for all types of vehicle should be equivalent to each other at each diffusion rate.

The marginal social benefit, $msben^a$, may be expressed as:

$$msben^a(p, \mathbf{x}^*) = \frac{1}{\bar{n}} \sum_{k=1}^{m} \left(-\frac{F_p}{F_{x_k^*}} \frac{\partial}{\partial x_k^*} sben^a{}_k(p, \mathbf{x}^*)\right),$$

$$\text{where } F_p = \frac{\partial}{\partial p} F(p, \mathbf{x}^*), \quad F_{x_k^*} = \frac{\partial}{\partial x_k^*} F(p, \mathbf{x}^*). \tag{6}$$

The above system of equations (4) and (5) cannot be analytically solved for $\mathbf{x}^*$. Thus, we solve it numerically via Newton's method, for fixed values of p in Eqs. (4) and (5). We also derive a value for Eqs. (3) and (6) at a diffusion rate p by plugging p and the corresponding $\mathbf{x}^*$ value.

3.1.2 V2Vs

Moving to V2Vs, the characteristic economic feature of these systems is that they are only able to prevent accidents when both the vehicles involved are equipped with the system. However, they can avoid accidents independently of whether the user's vehicle would be the primary or the secondary party. Thus, the benefits $U_{i,k}^c$ enjoyed by individual i using a vehicle of type-*k* equipped with a V2V may be defined as follows:

$$U_{i,k}^{c}(x_{i,k}) = U_{i,k}^{c1}(x_{i,k}) + U_{i,k}^{c2}(x_{i,k}),$$

where $U_{i,k}^{c1}(x_{i,k}) = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t}(x_{i,k} * (\sum_{l=1}^{m}(\sum_{j=1}^{q_l} x_{j,l} * a_{k,l} * v_{k,l}))$,

$$U_{i,k}^{c2}(x_{i,k}) = \sum_{t=0}^{t_k} \frac{1}{(1+r)^t}(x_{i,k} * (\sum_{l=1}^{m}(\sum_{j=1}^{q_l} x_{j,l} * a_{l,k} * w_{l,k})). \quad (7)$$

Here, $U_{i,k}^{c1}$ denotes the benefit from avoiding accidents at which individual i is the primary party while $U_{i,k}^{c2}$ does the benefit from avoiding accidents at which individual i is the secondary party. 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 system (q_l is equal to n_l when the diffusion rate of the system in vehicles of type-*l* is equal to one). Thus, the quantity $\sum_{j=1}^{q_l} x_{j,l}$ is the annual travel distance of such vehicles. The total amount of the social benefits, $sben^c$ where the diffusion rate of the system is p, may be expressed as:

$$sben^c(p, \mathbf{x}^*) = \sum_{k=1}^{m} sben^c{}_k(p, \mathbf{x}^*) = \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} U_k^c(x_k)\, d_k(x_k)\, dx_k,$$

where $\mathbf{x}^* = (x_1^*, , x_k^*, , x_m^*)$, (8)

under the condition that vectors (p, $\mathbf{x}^*$) satisfy the following system:

$$F(p, \mathbf{x}^*) = \frac{1}{\bar{n}}(\sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} d_k(x_k)dx_k) - p = 0, \text{ where } \bar{n} = \sum_{k=1}^{m} n_k, \quad (9)$$

$$U_1^c(x_1)|_{x_1^*(p)} = \ldots = U_k^c(x_k)|_{x_k^*(p)} = \ldots = U_m^c(x_m)|_{x_m^*(p)}. \quad (10)$$

The marginal social benefit, $msben^c$, may be expressed as:

$$msben^c(p, \mathbf{x}^*) = \frac{1}{\bar{n}} \sum_{k=1}^{m} (-\frac{F_p}{F_{x_k^*}} \frac{\partial}{\partial x_k^*} sben^c{}_k(p, \mathbf{x}^*)),$$

where $F_p = \frac{\partial}{\partial p} F(p, \mathbf{x}^*)$, $F_{x_k^*} = \frac{\partial}{\partial x_k^*} F(p, \mathbf{x}^*)$. (11)

3.1.3 Combinations of standalone systems and V2Vs

Next, we introduce a formula for the marginal value of the benefits related to combinations of standalone systems and V2Vs. On the one hand, the private benefit $U_{i,k}^{dual\_1}$ for individual *i* using a vehicle of type-*k* equipped with a combined system, under the condition of no overlap between the types of accidents prevented by standalone systems and V2Vs, may be defined as:

$$U_{i,k}^{dual\_1}(x_{i,k}) = \gamma_k U_{i,k}^{a}(x_{i,k}) + (1-\gamma_k) U_{i,k}^{c}(x_{i,k}) \quad (12)$$

Here, γ_k denotes standalone systems' coverage rate for vehicles of type-*k* in the sum of traffic accident losses. On the other hand, $U_{i,k}^{dual\_2}$, the benefit when V2Vs offer 100% accident coverage and standalone systems offer some coverage in parallel, may be defined as:

$$U_{i,k}^{dual\_2}(x_{i,k}) = \gamma_k (U_{i,k}^{a}(x_{i,k}) - U_{i,k}^{c1}(x_{i,k})) + U_{i,k}^{c}(x_{i,k}) \quad (13)$$

The sum of the social benefits, $sben^{dual\_1}$ and $sben^{dual\_2}$, may be expressed as:

$$sben^{dual\_1}(p, \mathbf{x}^*) = \sum_{k=1}^{m} sben^{dual\_1}{}_k(p, \mathbf{x}^*)$$

$$= \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} U_k^{dual\_1}(x_k)\, d_k(x_k)\, dx_k + \gamma_k \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} E_k^{a}(x_k)\, d_k(x_k)\, dx_k \quad (14)$$

$$sben^{dual\_2}(p, \mathbf{x}^*) = \sum_{k=1}^{m} sben^{dual\_2}{}_k(p, \mathbf{x}^*)$$

$$= \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} U_k^{dual\_2}(x_k)\, d_k(x_k)\, dx_k + \gamma_k \sum_{k=1}^{m} n_k \int_{x_k^*}^{\infty} E_k^{a}(x_k)\, d_k(x_k)\, dx_k \quad (15)$$

$msben^{dual\_1}$ and $msben^{dual\_2}$ are defined analogously to the case of standalone system.

3.2. Data

The data we use for the variables in the equations above refer to Japan and (mainly) to the year 2012.
First, numbers of traffic accidents and casualties are obtained through a traffic accident data aggregator provided by the Japan's Institute for Traffic Accident Research and Data Analysis (ITARDA).
Second, losses for a victim whose body damage is death, serious or slight injury are set based on the Cabinet Office (2012). The Cabinet Office (2012) categorizes injuries into "injuries with residual disability" and "injuries without residual disability," while the ITARDA's traffic accident data classify injuries into "serious injuries" and "slight injuries." Here, we assume that the ITARDA category of "serious injuries" corresponds to "injuries with residual disability" in the Cabinet Office (2012), while the "slight injuries" category corresponds to "injuries without residual disability" in the Cabinet Office (2012). The 2009 values established by Cabinet Office (2012) are adjusted by using GDP-deflator. Losses referring to death, serious and slight injuries are set at 234,031 thousand yen, 17,471 thousand yen, and 1,776 thousand yen, respectively.
Third, we use the number of automobiles provided by the Japan's Automobile Inspection & Registration Information Association. Monthly travel-distance data from Japan Automobile Manufacturers Association (2014) are used to determine the parameters in the log-normal distribution of annual travel distances.
Finally, average vehicle life expectancies are set using estimated values in Miyoshi (2016). The average for standard-sized passenger vehicles for private use is set at 13.4 years and that for light passenger vehicles, at 15.6 years.

4. Effects of combination of standalone systems and V2Vs

We now compute the benefit from combination of standalone systems and V2Vs.
Here, we focus on how the curve for the benefit derived from marginal system user will shift when standalone and V2V systems—two quite distinct technologies are combined. The benefit derived from marginal system user includes the benefits enjoyed by public institutions, firms, and the others, and thus differ in this way from the marginal private benefit—that is, demand curve. However, we can think of the marginal private benefit as a fixed fraction of the benefit derived from marginal system user, and thus the actual demand curve will be of the same shape as that for the benefit derived from marginal system user. On this account, we believe that the major findings of the following discussion keep validity.

Figure 1 plots the benefits derived from marginal system user versus the market diffusion rate for accident-prevention systems. Here we have assumed that there is no overlap between the types of accidents that are prevented by standalone and by V2Vs—that is, any given type of accident may be prevented by one or the other systems, but not both—and the various curves in the figure correspond to various fractional accident coverage rates for the two systems. For example, the red-colored curve is for the case in which V2Vs are capable of preventing 100% of accidents (and thus no vehicles are equipped with standalone system devices), while the blue-colored curve is for the opposite extreme in which standalone systems prevent 100% of accidents (and no vehicles are equipped with V2V devices). The remaining curves are for intermediate cases in which standalone systems cover some fraction of accidents and V2Vs cover all other accidents. For a V2V coverage rate of 100%, the curve for the benefit derived from marginal system user has an inverted-U shape. The reason for this is that, in the case of V2Vs, at low market-diffusion rates there are few other vehicles with whom to exchange accident-preventing data, and thus the benefit derived from marginal system user is extremely small—even for users who travel long distances and thus have relatively higher probabilities of experiencing accidents. Suppose the price of a set of devices is equal to 80 thousand yen. In this case, the curve for the benefit derived from marginal system user intersects the price curve at the two points f_1 and f_2. If the curve for the benefit derived from marginal system user were identical to the marginal private benefit curve (demand curve), f_1 would correspond to a market diffusion rate well known as the 'critical mass:' a dynamically unstable equilibrium point. If the diffusion rate rises slightly above f_1, the diffusion rate will automatically converge to f_2, a stable equilibrium point. In contrast, if the diffusion rate falls below f_1, the diffusion rate will automatically converge to zero (Rohlfs, 1974).

In contrast, in the opposite extreme in which standalone systems cover 100% of accidents, the curve for the benefit derived from marginal system user is monotonically decreasing, as is observed for typical demand curves. This is because vehicles equipped with standalone systems enjoy accident-preventing benefit regardless of the fraction of other vehicles equipped with the system, and the benefit derived from marginal system user is large for users with long travel distances and correspondingly high accident probabilities. We see also that, for the 100% standalone-coverage scenario, the benefit derived from marginal system user at high market-diffusion rates are smaller than those for the 100% V2V coverage scenario. The reason for this is that, for V2Vs, the number of other drivers with whom data may be exchanged increases as the market-diffusion rate rises, increasing the benefit derived by each user. Moreover, a feature of the V2V is that it enables prevention accidents in the case where the user would be the secondary party of an accidents. Neither of these effects is present for standalone systems.

We next consider scenarios in which both standalone and V2Vs are in use. Figure 1 shows results for three cases, in which standalone systems are capable of preventing {10%, 30%, 50%} of accidents (leaving the remaining {90%, 70%, 50%} of accidents covered by V2Vs). The benefit derived from marginal system user for these cases are hybrid versions of the curves for the two extreme cases (100% coverage by one or the other system) considered above; as the coverage of standalone systems grows, the curves increasingly resemble the curve for the case of 100% standalone-system coverage. In contrast, as the coverage of standalone systems decreases, the curve approaches that for the case of 100% V2V coverage. The important point here is that, at a standalone-system coverage rate of 10%, the curve still assumes the inverted-U shape observed for the V2V in isolation; however, at a larger standalone-system adoption rate of 30%, the curve exhibits a monotonically decreasing trend similar to what is observed for standalone systems in isolation. This indicates that the combined use of the two types of system solves the critical mass problem that exists for V2Vs in isolation. Even more interesting is the fact that, among the three scenarios in which the curve is monotonically decreasing, the scenario resulting in the highest market-diffusion rate—at the price of a set of devices is equal to 80 thousand yen—would be the case in which the standalone-system coverage rate is the smallest, namely 30%, followed by the cases of 50% and 100% standalone-system coverage supposing that thee curve for the benefit derived from marginal system user were identical to the demand curve. On the other hand, at the price of a set of devices is to 100 thousand yen, we find that market diffusion would be maximized for the scenario in which standalone systems cover 100% of accidents, followed by the cases of 50% and 30% standalone-system coverage. This is precisely the reverse of the ordering for the case where the price of a set of devices is equal to 80 thousand yen.

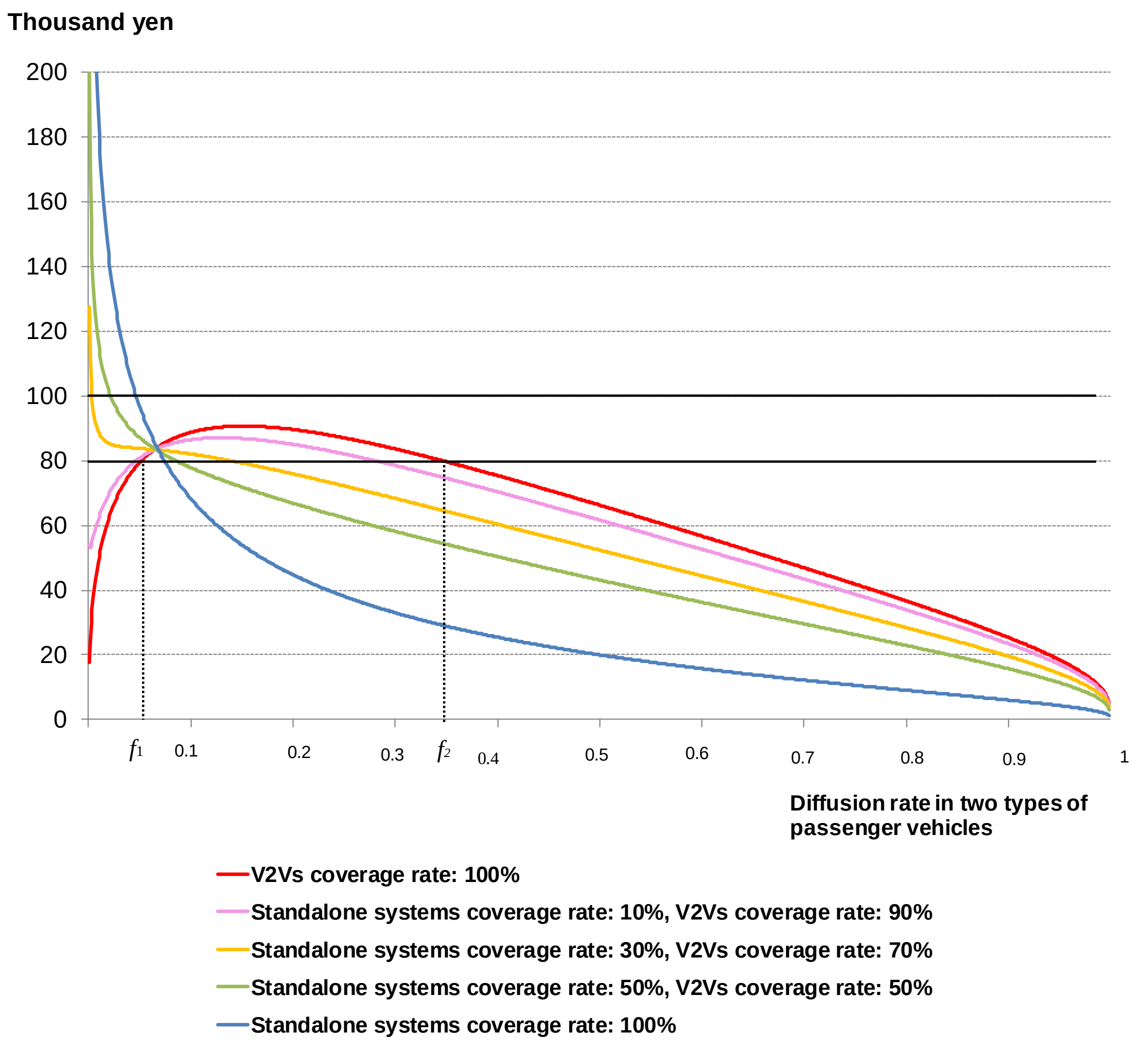

Figure 1 Benefit derived from marginal system user (assuming no overlap between the types of accidents prevented by the two systems)

Figure 2 plots the marginal social benefit versus the market diffusion rate for accident-prevention systems. The amount of the marginal social benefit for the case of 100% V2V coverage is approximately two times as much as that of the benefit derived from marginal system user for the same case. It is because the marginal social benefit includes the benefit enjoyed by not only the marginal user but also already equipped user. As the coverage of standalone systems increases, the ratio of the amount of the marginal social benefit to that of the benefit derived from marginal system user increases. It is because standalone systems provide the secondary parties with accident prevention benefits.

The optimal diffusion rate is at the intersection of the marginal social benefit curve and the marginal social cost curve (here, price curve). It is necessary to provide subsidies to system users to realize the optimal diffusion rate.

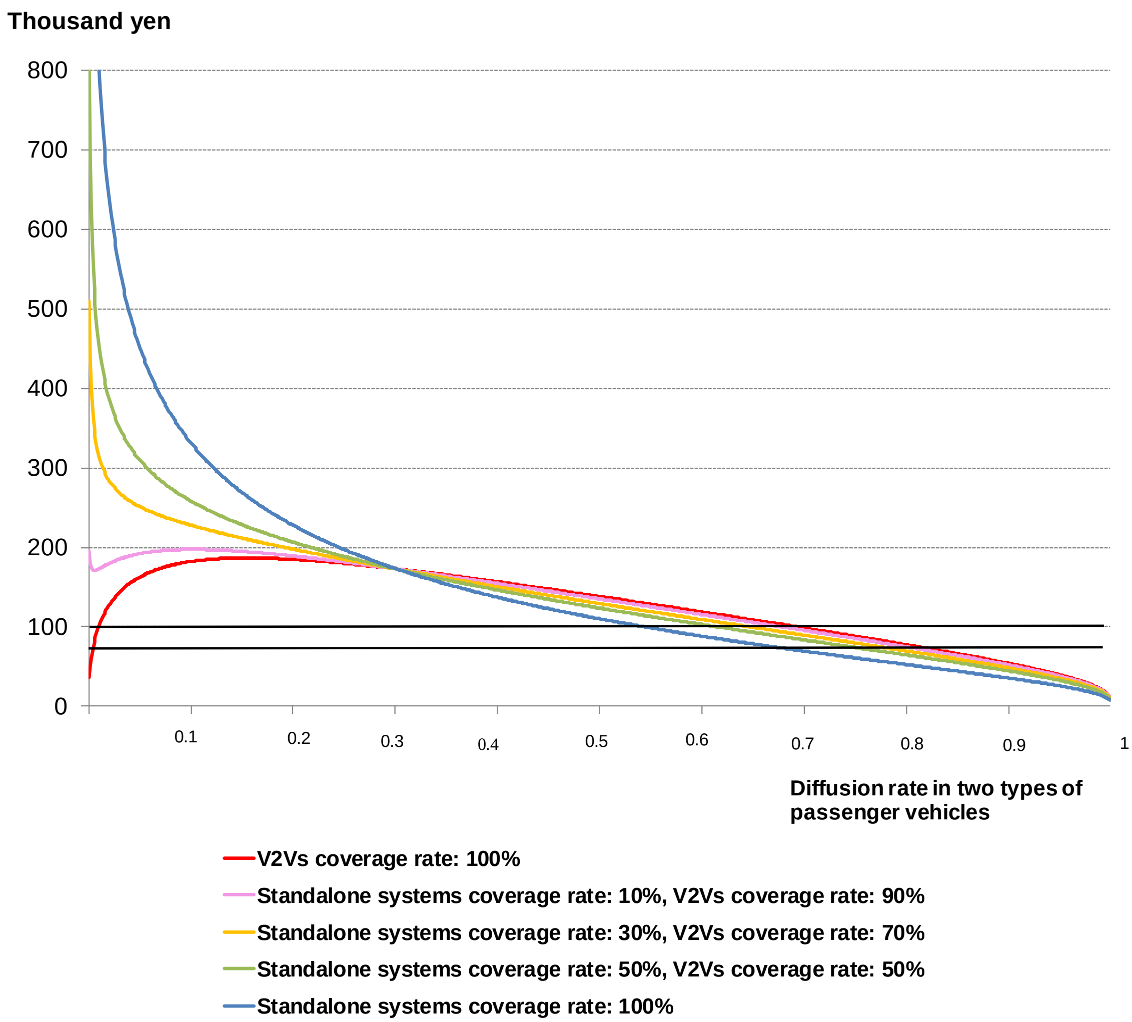

Figure 2 Marginal social benefit (assuming no overlap between the types of accidents prevented by the two systems)

Next, assuming that V2Vs offer 100% accident coverage, we suppose that standalone and V2Vs are combined in such a way that the accident-prevention features of standalone systems overlap with those of V2Vs, and we ask how the benefit derived from marginal system user changes in each of four cases: standalone-system accident coverage rates of 10%, 30%, 50%, and 100%. Here a value of 100% for the standalone system coverage rate signifies that all accidents can be prevented both by V2Vs and by standalone systems. The advantage of combining standalone and V2Vs with this sort of redundancy is that it allows standalone systems to offer high benefit at early stages in which adoption of accident-prevention systems is not widespread, while still facilitating the high benefit offered by V2Vs at higher market-diffusion rates.

From Figure 3, we see that the benefit derived from marginal system user for low system-adoption rates are shifted significantly upward for standalone-system coverage rates of 30% or greater without making the curves corresponding to higher system-adoption rates shift downward.

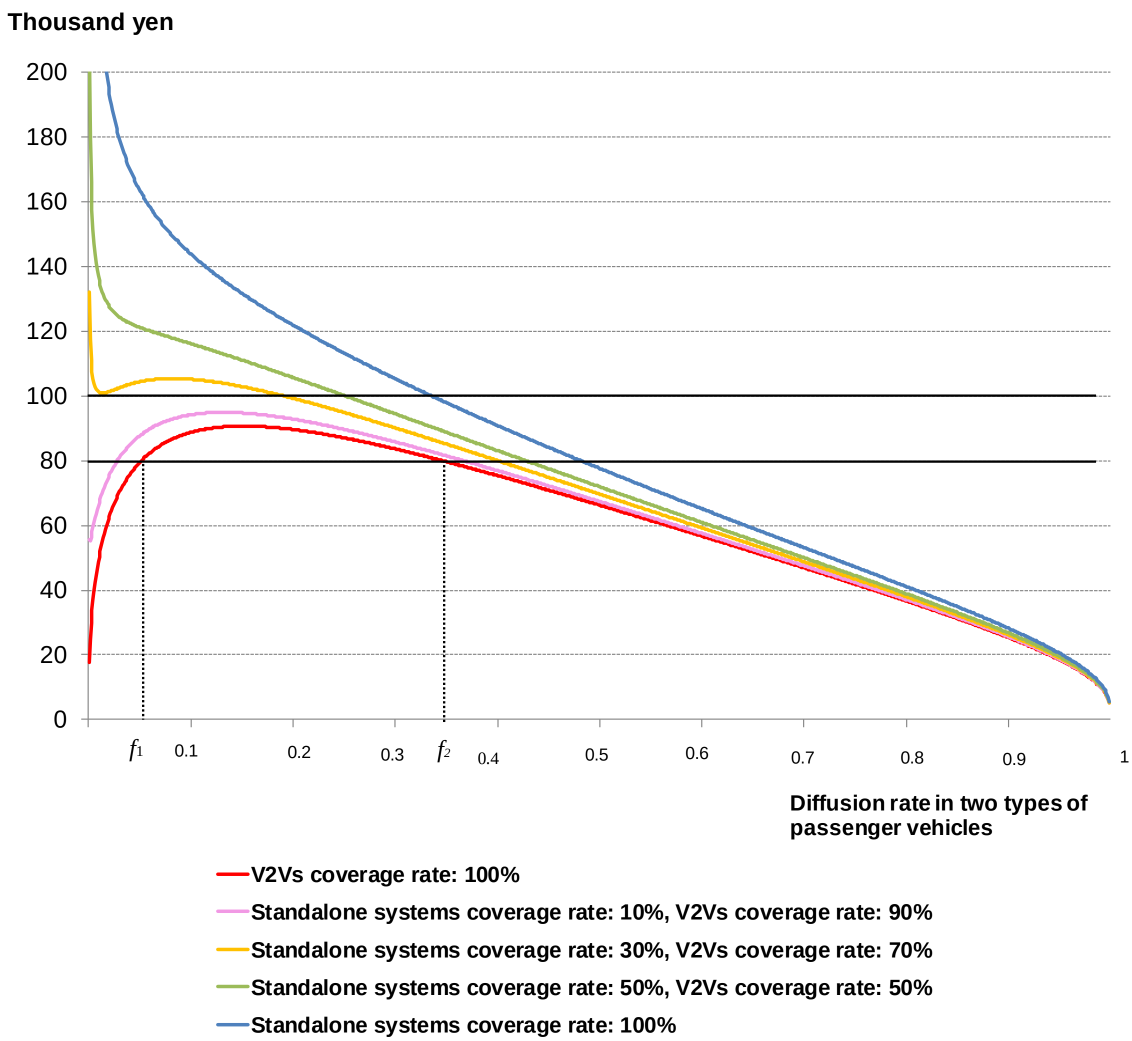

Figure 3 Benefit derived from marginal system user (assuming some overlap between the types of accidents prevented by the two systems)

Figure 4 plots the marginal social benefit versus the market diffusion rate for accident-prevention systems. As in the case of zero overlap**,** the ratio of the marginal social benefit to that of benefit derived from marginal system user increases as the coverage of standalone systems increases.

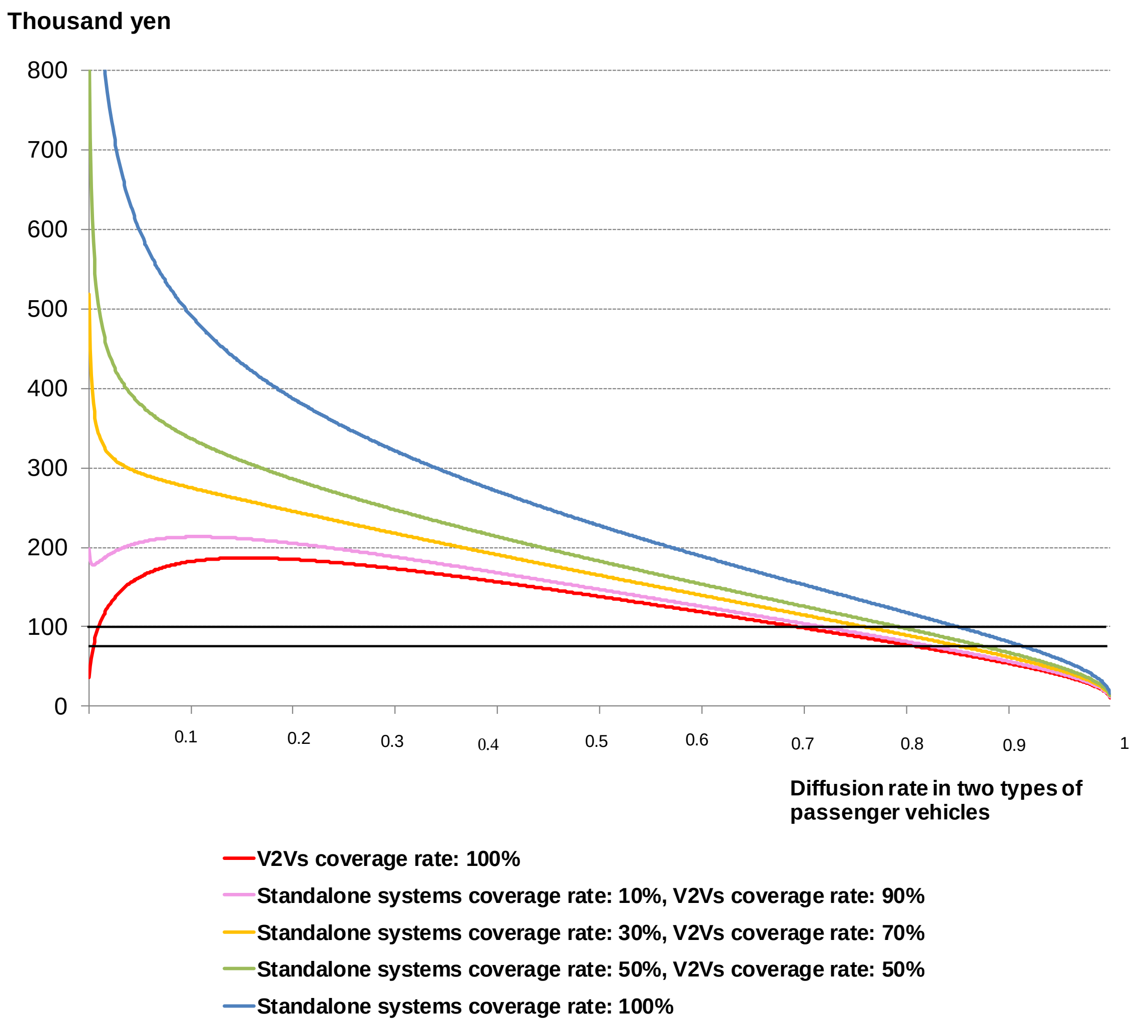

Figure 4 Marginal social benefit (assuming some overlap between the types of accidents prevented by the two systems)

5. Discussion and conclusions

In this paper, we considered the simultaneous use of standalone and V2V accident-prevention systems and analyzed the ways in which the combination of technologies affects the shape of the marginal benefit curves for system devices. In this final section, we discuss the implications of our results both for system and for policy development.

With regard to the effects of combining standalone systems and V2Vs, the most important finding of our study is that the combination significantly facilitates solving the critical-mass problem for V2Vs. We can consider the critical-mass problem solved for standalone-system coverage rates of 30% or greater.

We next note that, for the purposes of achieving higher market diffusion rates, it may be advantageous for standalone and V2Vs to have some overlap in the types of accidents they prevent, rather than a strict separation of their respective coverage regions. In the case where there is no overlap between the systems, once we are past the stage of low market diffusion, we find that the the benefit derived from marginal system user is lower when the two systems are combined than for the case of V2Vs alone. We may assume that the relative positioning of the demand curves will be similar, and thus—if there is no difference in price—the market-diffusion rate will be lower in the combined scenario than for the case of V2Vs alone. In contrast, for the scenario where we allow overlap between the types of accidents preventable by the two systems, the benefit derived from marginal system user for low system-adoption rates are shifted significantly upward without making the curves corresponding to higher system-adoption rates shift downward. Because the extent of the overlap is tied directly to price, we can say—in general, if not in all cases—the market diffusion rate may be higher for this combined, overlapping scenario than for the case of V2Vs in isolation or for scenarios in which the types of accidents preventable by the two systems are strictly separated.

Acknowledgements
This work was supported by JSPS Grants-In-Aid for Scientific Research #25281071 and #16K12830.

References

1. Japan Automobile Manufacturers Association (2014). Passenger car market trends in Japan 2013 (in Japanese).
2. Japan's Cabinet Office (2012). Report of the survey on economic analysis on the damage and loss of road traffic accidents (in Japanese).
3. Jia, D. and D. Ngoduy (2016). Enhanced cooperative car-following traffic model with the combination of V2V and V2I communication, *Transportation Research Part B*, vol. 90, pp. 172–191
4. Kii, M. and H. Miyoshi (2011). Market penetration of safety-related ITSs, in H. Miyoshi and M. Kii (eds.), *Technological innovation and public policy: The automotive industry*, Palgrave Macmillan, 2011
5. Miyoshi, Hiroaki (2016). Diffusion policies of automated driving systems: Rear-end collision-prevention Systems, *ITEC Working Paper Series*, 16-02
6. Rohlfs, J. H. (1974). A theory of independent demand for a communications service, *Bell Journal of Economics and Management Science*, vol. 5, pp. 16-37.
7. Shin, L. and P.D. Prevedouros (2016). Autonomous and connected cars: HCM estimates for freeways with various market penetration rates, *Transportation Research Procedia*, vol. 15, pp.389-402.
8. Vegni, A. M. and T. D.C. Little (2011) Hybrid vehicular communications based on V2V-V2I - CiteSeerX *International Journal of Vehicle Information and Communication Systems*, vol. 2. , pp. 213-231.
9. Li, T., Kockelman, K. (2016). Valuing the safety benefits of connected and automated vehicle technologies. Paper no. 16-1468. In presented at the *95th Meeting of the Transportation Research Board*, Washington, DC.