Combined Vehicular Communication and its Performance

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Abstract. The performance of the vehicular communication used for Intelligent Transport Systems is investigated. Intervehicle communication (IVC) and combined vehicular communication implemented by IVC and additional communication media are studied and their performance is explicitly described. Through the numerical examples, it is shown that performance varies according to parameter values such as the mean space headway, the speed of the vehicles, and the penetration ratio of the IVC device. To achieve a certain level of performance, I propose a) a design of the information delivery delay of additional communication media and b) a method determining the appropriate delay.

Keywords: vehicular communication, Intelligent Transport Systems, intervehicle communication.

1 Introduction

Today, traffic safety is a major problem all over the world. Therefore, special attention is paid to the technologies that reduce the number of accidents. The introduction of vehicular communication technology is expected to be a solution to the problem. Vehicular communication can deliver a variety of information: (i) basic safety information such as position of vehicle, its speed, and abnormal road conditions, (ii) warning information, (iii) infotainment information such as services, and traffic information, (iv) routing information for routing protocols, and (v) interpersonal information, such as profiles of drivers and passengers [10]. At present, infotainment information is already being provided through existing telecommunication networks such as cellular networks and satellite networks. R&D is, thus, mainly focused on providing information through intervehicle communication (IVC) and vehicle-to-road communication (VRC). In particular, IVC, which mainly uses short range millimeter radio and infrared laser [1], for delivering basic safety information (e.g., speed, direction, space headway, and slipperiness [5]), road characteristics including obstacles on the roadway detected by an onboard camera and/or warning information is one of the hottest topics in the Intelligent Transport Systems (ITS) field.

The basic properties of IVC performance are investigated in this paper. Efforts similar to this paper, that is, investigations of the basic properties of IVC performance, have been made using simulation studies. By using a microscopic simulator, the performance
of delivering information between vehicles is evaluated \[11\]. For example, the lifetime distribution of a communication path between two vehicles and the number of vehicles that can be reached by a broadcast message are evaluated. Through their simulation, interesting results are found. Comparing the high and low traffic density cases, we see that the number of vehicles that can be reached by a broadcast path in the high-density case is much larger than that in the low-density case. Even in the high-density case, a broadcast message may reach a large number of vehicles but has about the same chance to reach only a small number of vehicles. In both cases, broadcasting information via multihop IVC to a large number of vehicles is not a reliable method. Similar simulation results are also presented in \[2\]. In \[3\], a simulation is used to evaluate the performance of accident information delivery. A zone-of-relevance is defined and the ratio of equipped vehicles that can receive information in the zone-of-relevance is evaluated through the simulation. (An effort to build a simulator for the distribution of information via IVC is described in \[7\].)

The reason for the difficulties in delivering information to vehicles via multihop IVC is “the scattered communication effect” \[10\]. The following is an explanation of the scattered communication effect. Each vehicle participating in IVC must be equipped with a special in-vehicle device (wireless transceiver). However, because of the slow introduction and adoption of ITS, the deployment rate of such devices is low. This results in fragmentation of the network. A similar sort of fragmentation occurs in the case where short-range radio communication is used. In addition, when vehicle density is low, the vehicles may be spread far apart causing them to be outside of the transmission range of a vehicle.

One method bridging the gaps of IVC networks and mitigating the scattered communication effect is to forward data via another communication medium. In \[4\], vehicle-to-road communication (VRC) is used in combination with IVC. IVC and VRC are merged in order to obtain an integrated environment where traffic participants exchange safety-related messages.

The use of additional media to compensate for the IVC for driver assistance information delivery (Fig. 1) is also presented in this paper. VRC may be used as this additional medium but the existing networks such as cellular phone networks are also possible. These additional media are not identified in this paper, but it is assumed that it takes more time to deliver the information because these additional media require indirect information delivery (and may require data processing at the data center).

## 2 Model

A vehicular traffic flow running unidirectionally in a single lane is considered in this paper (Fig. 2-A). Running vehicles are classified into two categories \[8\]. The vehicles in the first category run freely and independently from other vehicles. Their space headway is normally large. On the other hand, the drivers of the vehicles in the second category try to follow the preceding vehicle. Their space headway is normally short. This paper uses the expressions, category-1 vehicle and category-2 vehicle, respectively.

The space headway between a category-1 vehicle and the preceding vehicle is assumed to have a probabilistic density function \(f(\cdot)\) with mean \(\bar{f}\). (Let \(F(\cdot)\) be the cumulative distribution function and \(F^*(s)\) be the Laplace-Stieltjes transform (LST) of \(f(x)\).) The
space headway of a category-2 vehicle to the preceding vehicle is assumed to have a probabilistic density function \( h(\cdot) \) with mean \( \bar{h} \). (Let \( H(\cdot) \) be its cumulative distribution function and \( H^*(s) \) be the Laplace-Stieltjes transform (LST) of \( h(x) \).) According to the field study, the space headway between a category-1 vehicle and the preceding vehicle is exponentially distributed and that between a category-2 vehicle and the preceding vehicle is the \( k \)-Erlang distribution with \( k = 5, 6 \) \([8]\). That is, \( f(x) = e^{-x}/\bar{f} \) and \( h(x) = (k/\bar{f}) x^{k-1} e^{-x/\bar{f}}/(k-1)! \). In the numerical examples in this paper these distributions are assumed and \( k = 5 \).

Assume that the next vehicle after a category-1 vehicle is a category-2 vehicle with probability \( a \) or is a category-1 vehicle with probability \( 1 - a \). Assume that the next vehicle after a category-2 vehicle is a category-1 vehicle with probability \( b \) or is a category-2 vehicle with probability \( 1 - b \) (Fig. 2-B). Thus, the stationary probability that a vehicle is a category-1 vehicle is \( b/(a + b) \) and that for a category-2 vehicle is \( a/(a + b) \).

Each vehicle is traveling with fixed velocity \( v \) and equipped with vehicular communication transceivers with probability \( c \). Vehicular communication will be performed by means of IVC. (Vehicular communication using additional communication media is referred to in the subsequent section.) IVC, which is implemented with short-range communication systems, can send necessary information to the following vehicle immediately if the distance to the following vehicle is shorter than the communication range \( r \). It is assumed in this paper that if there are vehicles between two vehicles equipped with communication devices, the direct communication between them is impossible with IVC because of the sharp directivity of IVC, even if they are within the range \( r \). However, if a vehicle between them is equipped with a communication device, they are assumed to communicate via multihop IVC.

It is assumed in this paper that the delivered information is basic safety information such as road characteristics and obstacles on the road. Information about events that happen uniformly on the road must be detected by a vehicle and sent to the vehicle immediately following. Thus, the probability that a vehicle encounters the event is proportional to the space headway between the vehicle and the preceding vehicle.
3 Analysis of combined communications

Vehicular communications both with IVC and with additional communication means are analyzed in this section. Unlike IVC, vehicular communication using additional communication media such as cellular networks and satellite networks enables necessary information to be uploaded and downloaded independently of space headway. However, immediate communication may not be possible via other means. Normally, some pieces of information are put together and sent to the information center, and they are distributed to all the vehicles, if the existing network is used. It is assumed in this paper that the time for sending the necessary information and distributing it is exponentially distributed with mean $u$.

This section investigates whether, if a vehicle detects abnormality on the road, vehicles behind the detecting vehicle can receive the detected information by using IVC or additional communication media before they pass the place where the abnormal event happens.

Let $S(x)$ be the matrix denoting the probability that a vehicle can send information successfully to the following vehicle via IVC and that the space headway between them is $x$. Then,

$$S(x) = \begin{cases} 
  c \left( \frac{(1-a)f(x)}{b f(x)} \right), & \text{if } r \geq x \\
  a h(x) \left( \frac{1}{b} \right), & \text{if } r < x
\end{cases}
$$

The $(i,j)$-element of the two $\times$ two matrix corresponds to the state transition from a category-$i$ vehicle to a category-$j$ vehicle ($i,j = 1, 2$). Let $S^*(s)$ be the LST of $S(x)$. Then,

$$S^*(s) = c \left( \frac{(1-a)\tilde{F}(s, r)}{b \tilde{F}(s, r)} \right) \frac{a \tilde{H}(s, r)}{(1-b)\tilde{H}(s, r)},$$

where $\tilde{F}(s, r) = \int_0^s e^{-sx} f(x) \, dx$ and $\tilde{H}(s, r) = \int_0^s e^{-sx} h(x) \, dx$.

By using $S^*(s)$, we can derive the matrix $S_n(x)$ denoting the probability that a vehicle can send information successfully to the following $n$ consecutive vehicles or more via IVC and that the total space headway between the originating vehicle and the $n$-th vehicle is $x$. Let $S_n^*(s)$ be the LST of $S_n(x)$ Then,

$$S_n^*(s) = (S^*(s))^n.$$ (3)

On the other hand, let $T(x)$ be the matrix denoting the probability that a vehicle fails to send information to the following vehicle via IVC and that the space headway between them is $x$. Then,

$$T(x) = \begin{cases} 
  (1-c) \left( \frac{(1-a)f(x)}{b f(x)} \right), & \text{if } r \geq x \\
  \left( \frac{(1-a)\tilde{F}(s, r)}{b \tilde{F}(s, r)} \right), & \text{if } r < x
\end{cases}$$

Let $T^*(s)$ be the LST of $T(x)$. Then, using $\int_0^\infty e^{-sx} f(x) \, dx = F^*(s) - \tilde{F}(s, r)$ and $\int_0^\infty e^{-sx} h(x) \, dx = H^*(s) - \tilde{H}(s, r)$, we can derive $T^*(s)$.

$$T^*(s) = \left( \frac{(1-a)(F^*(s) - c\tilde{F}(s, r))}{b(F^*(s) - c\tilde{F}(s, r))} \right) \frac{a(H^*(s) - c\tilde{H}(s, r))}{(1-b)(H^*(s) - c\tilde{H}(s, r))}$$

(5)
By using $T^*(s)$ and $S^*_n(s)$, we can derive the matrix $W_{n,m}(x)$ denoting the probability that a vehicle can send information successfully to the following $n$ consecutive vehicles, the $n+1$-th,..., $n+m$-th vehicles fail to receive information via IVC, and that the total space headway between the originating vehicle and the $(n+m)$-th vehicle is $x$. Let $W^*_n(s)$ be the LST of $W_{n,m}(x)$. Then, for $n \geq 0$ and $m \geq 1$,

$$W^*_{n,m}(s) = S^*_n(s)T^*(s)(D^*(s))^{m-1},$$

where $D^*(s)$ is the LST of the matrix $D(x)$ denoting the probability that the space headway to the following vehicle is $x$ and given by the following.

$$D^*(s) = \begin{pmatrix} (1-a)F^*(s) & aH^*(s) \\ bF^*(s) & (1-b)H^*(s) \end{pmatrix}$$

Now we are in a position to investigate the performance of the combined communications: IVC with additional communication media. Note that these additional communication media cause a delay, $t$, with mean, $u$, and that vehicles run at a constant speed, $v$. Therefore, to send information about what is happening on the road to vehicles before they pass the point at which something happens (the target point), IVC must be used for the vehicles within a length, $vt$, from the vehicle detecting something that has happened. (For simplicity, this paper assumes that all vehicles can receive broadcast messages through this additional communication media. Thus, this additional communication media can send information to all vehicles farther away than $vt$ from the vehicle detecting something that has happened before they pass the target point.) Thus, the performance measure is how many vehicles can (cannot) receive information via IVC among vehicles within a length, $vt$, from the detecting vehicle. In the following, we call the length, $vt$, from the detecting vehicle, the target range. The target range, $vt$, is an exponentially distributed random variable with mean, $uv$.

Let $q_{n,m}$ be the probability that there are $m+n$ vehicles in the target range and that a vehicle can send information successfully to the following $n$ consecutive vehicles and fail to send the information to the $n+1$-th,..., $n+m$-th vehicles via IVC in the target range. For $m = n = 0$, the vehicle following the detecting vehicle is out of the target range. Therefore,

$$q_{0,0} = \int_{t=0}^{\infty} \frac{1}{u} e^{-t/u} \int_{y=vt}^{\infty} \mathbf{v}D(y)\mathbf{1}_2dydt.$$

Here, $y$ is the space headway of the vehicle following the detecting vehicle, $\mathbf{1}_2 = (1,1)^T$, and $\mathbf{v}$ is the probability vector of the category of a vehicle finding an event on the road and given by $\mathbf{v} = (b\bar{f}/(b\bar{f} + a\bar{h}) \quad a\bar{f}/(b\bar{f} + a\bar{h}))$.

For $m = 0, n > 0$, $n$ consecutive vehicles after the detecting vehicle succeed in receiving information, and they are within the target range. The $n+1$-th vehicle is out of the target range. Thus,

$$q_{n,0} = \int_{t=0}^{\infty} \frac{1}{u} e^{-t/u} \int_{x=0}^{vt} \int_{y=vt-x}^{\infty} \mathbf{v}S^*_n(x)D(y)\mathbf{1}_2dydxdt.$$

Here, $x$ is the total space headway between the detecting vehicle and the $n$-th vehicle, and $y$ is the space headway of the $n+1$-th vehicle.
Similarly, for \( n \geq 0, m \geq 1 \),
\[
q_{n,m} = \int_{t=0}^{\infty} \frac{1}{u} \int_{x=0}^{\infty} \int_{y=vt-x}^{\infty} vW_{n,m}(x) D(y) 1_2 dy dx dt.
\]
Therefore,
\[
q_{0,0} = 1 - \{(1 - a)\tilde{f} + a\tilde{h} b F^*(\frac{1}{uv}) + (b\tilde{f} + (1 - b)\tilde{h} a H^*(\frac{1}{uv}))/(a\tilde{h} + b\tilde{f})\},
\]
for \( n > 0 \),
\[
q_{n,0} = \nu c^n \left(\frac{1 - (1 - a)\tilde{F}(\frac{1}{uv}, r)}{1 - b F^*(\frac{1}{uv})} - \frac{aH^*(\frac{1}{uv})}{1 - (1 - b)H^*(\frac{1}{uv})}\right)^n Q(a, b, F, H, uv),
\]
where
\[
Q(a, b, F, H, uv) = \left(\frac{1 - (1 - a)F^*(\frac{1}{uv}) - a H^*(\frac{1}{uv})}{1 - b F^*(\frac{1}{uv}) - (1 - b) H^*(\frac{1}{uv})}\right).
\]
Similarly, for \( n \geq 0, m \geq 1 \),
\[
q_{n,m} = \nu (S^*(\frac{1}{uv}) - T^*(\frac{1}{uv}))(D^*(\frac{1}{uv}))^{m-1}Q(a, b, F, H, uv).
\]
In particular, by using \( q_{n,m} \), \( P_{suc} = \text{Pr} \) (Information can be delivered to all vehicles before they pass the target point) and \( P_{fail}(m) = \text{Pr} \) (information is not delivered to \( m \) vehicles before they pass the target point) are given by the following equations \((m > 0)\).
\[
P_{suc} = \nu \left(\frac{1 - (1 - a)\tilde{F}(\frac{1}{uv}, r)}{1 - b\tilde{F}(\frac{1}{uv}, r)} - \frac{ac\tilde{H}(\frac{1}{uv}, r)}{1 - c(1 - b)\tilde{H}(\frac{1}{uv}, r)}\right)^{-1} Q(a, b, F, H, uv)
\]
\[
P_{fail}(m) = \nu (I - S^*(\frac{1}{uv}))^{-1} T^*(\frac{1}{uv}))(D^*(\frac{1}{uv}))^{m-1}Q(a, b, F, H, uv)
\]

4 Design and control of delay

The previous section indicates that the vehicular communication performance depends on various parameters. Thus, to attain a certain level of performance (for example, a certain objective value of \( P_{suc} \)) for various situations, it is effective to adjust some parameters to be adaptive to such situations.

Based on the measurement of the space headway, this section describes the design of delay, \( u \), of the additional communication media of IVC. Particularly when the delay in collecting data, putting them together, and sending them is a dominant portion of the delay, \( u \), it is possible that an additional communication provider controls the delay, \( u \). That is, the delay, \( u \), can be a control parameter and it is significant to set \( u \) at an appropriate value depending on the conditions such as highway or not, and/or rush hours or not, in order to attain a performance objective.

Consider the case in which the penetration ratio, \( c \), and the speed, \( v \), can be observed and the radio range, \( r \), is given. Thus, there are four unknown parameters: \( a, b, \tilde{f}, \) and \( \tilde{h} \). Estimating these parameters and determining an appropriate value for \( u \), this paper proposes the following method based on the space headway measurement.

Observe the space headway of individual vehicles, and calculate their average, \( O_1 \), and their second moment, \( O_2 \), the frequency \( O_3 \) of the space headway larger than \( X \), and the
average, \( O_4 \), of the number of the consecutive vehicles that are estimated as category-1 vehicles. Derivation of \( O_4 \) (the number of consecutive vehicles that are estimated as category-1 vehicles) is performed, assuming that a vehicle whose space headway is larger than the mean space headway \( \lambda^{-1} \) is a category-1 vehicle and that a vehicle whose space headway is smaller than the mean space headway is a category-2 vehicle.

Let \( f^*, h^*, a' \), and \( b' \) be the estimates of \( f^* \), \( h^* \), \( a \), and \( b \). This paper proposes that these estimates are derived by the following equations. (Here, \( k = 5 \) or 6. See 2. Model.)

\[
\begin{align*}
O_1 &= (b' f^* + a' h^*) / (a' + b') \\
O_2 &= 2 f^2 \frac{b}{a + b} + \frac{(k+1) h^2}{k} \frac{a'}{a + b} \\
O_3 &= e^{-X / f} \frac{b'}{a + b} \\
O_4 &= 1 / a'
\end{align*}
\]

(17)  
(18)  
(19)  
(20)

Here, \( X \) is an arbitrary value larger than the mean space headway and the numerical example sets \( X = 5 \times \) (the mean space headway).

If these parameter estimates \( a', b', f^* \), and \( h^* \) are determined by the equations above, they can be used to evaluate \( P_{\text{suc}} \) using Eq. (15) for various \( uv \). Thus, we can determine \( uv \) given the target value of \( P_{\text{suc}} \). (From a physical meaning, \( P_{\text{suc}}(uv \to 0) = 1 \) and \( P_{\text{suc}}(uv \to \infty) = 0 \). Thus, we can find \( uv > 0 \) satisfying a given target value of \( P_{\text{suc}} \). The uniqueness of the solution, however, has not been proven but \( P_{\text{suc}} \) is a decreasing function of \( uv \) for almost everywhere over the range of \( uv > 0 \) in the numerical examples. Therefore, there is no problem numerically.) Based on the determined \( uv \) and given \( v \), we can derive an appropriate value of \( u \). If this \( u \) can be derived and used according to the change of the estimation, the additional communication media and the combined vehicular communication can be a dynamically controlled system adaptive to the change in situations.

Eqs. (17) through (20) are proposed because of the following facts: \( E[O_1] = (b f + a h) / (a + b) \), \( E[O_2] = 2 f^2 \frac{b}{a + b} + \frac{(k+1) h^2}{k} \frac{a}{a + b} \), \( E[O_3] = \text{Pr}(x > X) \approx \text{Pr}(x > X | O_4) \) \( \text{Pr}(O_4) \) \( = e^{-X / f} \frac{b}{a + b} \), \( E[O_4] = 1 / a \), where \( O_4 \) denotes the event in which a vehicle is a category-1 vehicle. Here, the condition \( \{X >> \text{the mean space headway}\} \) is requested for the approximation in the equation on \( E[O_3] \), and \( O_4 \) is the average of the observed number of vehicles which are actually category-1 vehicles. Note that \( O_1, O_2, O_3 \) and \( O_4 \) are converged to their expectations \( E[\cdot] \) when the number of observed samples is large. Therefore, if \( E[O_4'] = E[O_4] \), the parameter estimates \( a, b, f^* \) and \( h^* \) take their true values \( a, b, f^* \) and \( h^* \) when the number of observed samples is large and \( X >> \) the mean space headway.

In the remainder of this section, we evaluate \( E[O_4] \) to investigate whether \( E[O_4'] = E[O_4] \) (that is, \( E[O_4] = 1 / a \)) or not. (The following section numerically evaluates the error of the estimation of \( P_{\text{suc}} \) with the parameter estimates.)

Let us consider the state consisting of two elements where the first denotes the category to which a vehicle belongs and the second denotes the estimated category to which a vehicle is observed to belong. Hence, there are four states: \((i, j) \) \((i, j = 1, 2)\). Using the Kronecker product, the transition probability matrix from \( \{(1, 1), (1, 2), (2, 1), (2, 2)\} \) to \( \{(1, 1), (1, 2), (2, 1), (2, 2)\} \) can be expressed by the following matrix \( \Theta \).

\[
\Theta = \begin{pmatrix}
(1 - a) \left(1 - F\left(\frac{X}{\lambda}\right)\right) & (1 - a) \left(F\left(\frac{X}{\lambda}\right)\right) & a \left(1 - H\left(\frac{X}{\lambda}\right)\right) & a H\left(\frac{X}{\lambda}\right) \\
\frac{b}{b} \left(1 - F\left(\frac{X}{\lambda}\right)\right) & b F\left(\frac{X}{\lambda}\right) & (1 - b) \left(1 - H\left(\frac{X}{\lambda}\right)\right) & (1 - b) H\left(\frac{X}{\lambda}\right)
\end{pmatrix} \otimes I_2
\]
The conditional state probability vector \( \theta_1 \) with the condition that a vehicle is observed as a category-1 vehicle is given by the following.

\[
\theta_1 = \left( \frac{b(1-F(1/\lambda))}{b(1-F(1/\lambda))+a(1-H(1/\lambda))} \frac{a(1-H(1/\lambda))}{b(1-F(1/\lambda))+a(1-H(1/\lambda))} \right)
\]  \hspace{1cm} (22)

Consider the event in which a vehicle is observed as a category-\( i \) vehicle and the vehicle that follows is observed as a category-\( j \) vehicle. The event is described as the transition from \((1,i)\) or \((2,i)\) to \((1,j)\) or \((2,j)\) where \(i, j = 1, 2\). For example, for \(i = j = 1\), the event is described as the transition from \((1,1), (2,1)\) to \((1,1), (2,1)\). Therefore, the probability \( p_1(n) \) that \( n \) consecutive vehicles are observed as category-1 vehicles is given by the following where \( n \geq 1 \). (Note that the first vehicle is observed as a category-1 vehicle because \( \theta_1 \) is used.)

\[
p_1(n) = \theta_1 R(a, b, F, H)^{n-1} \left( \begin{array}{cc}
(1-a) F(\frac{1}{H}) & a H(\frac{1}{H}) \\
 b F(\frac{1}{H}) & (1-b) H(\frac{1}{H})
\end{array} \right) 1_2
\]  \hspace{1cm} (23)

\[
R(a,b,F,H) = \left( \begin{array}{cc}
(1-a)(1-F(\frac{1}{H})) & a(1-H(\frac{1}{H})) \\
 b(1-F(\frac{1}{H})) & (1-b)(1-H(\frac{1}{H}))
\end{array} \right)
\]  \hspace{1cm} (24)

As a result, \( E[O_4] \), the expectation of the number of consecutive vehicles that are observed as category-1 vehicles, is as follows.

\[
E[O_4] = \theta_1 (I - R(a, b, F, H))^{-1} 1_2
\]  \hspace{1cm} (25)

Thus, \( E[O_4] \neq 1/a \).

When the number of observed samples of the space headway is large, the parameter estimates \( a', b', \bar{F}, \bar{h} \) satisfy Eqs. (17) through (20) replacing \( O_i \) with \( E[O_i], (i = 1, \ldots, 4) \). Based on the equations replacing \( O_i \) with \( E[O_i], (i = 1, \ldots, 4) \), we determine the parameter estimates and use them to evaluate \( P_{suc} \) in the following numerical examples.

5 Numerical examples

Now we investigate the effectiveness of the combined communication through the evaluation of \( P_{suc} \). In Figs. 3 through 6, the curves labeled “original” show \( P_{suc} \) based on Eq. (15), and the curves labeled as “estimated” show \( P_{suc} \) based on Eq. (15) with the estimated parameter values derived from Eqs. (17) through (20) replacing \( O_i \) with \( E[O_i], (i = 1, \ldots, 4) \).

The sensitivity of the mean space headway to \( P_{suc} \) is shown in Fig. 3, and that of the mean space headway of each category to \( P_{suc} \) is shown in Fig. 4. Here, the parameters \( a \) and \( b \) are fixed. Therefore, the ratio of the number of category-2 vehicles to the number of category-1 vehicles is fixed. In Fig. 3, the shape of the plotted curves is not monotonic. The reason for the increase in \( P_{suc} \) in Fig. 3 when the mean space headway increases is as follows. The increase of the mean space headway results in a larger space headway and a smaller number of vehicles in the target range. Thus, there is a possibility that all the vehicles in the target range can receive information though IVC. The reason for the decrease in \( P_{suc} \) is the increase of the probability that the vehicles are out of the radio range. The curves for “original” and those for “estimated” show good agreement and it is difficult for us to distinguish them. Therefore, we can make good estimation based on the observation \( O_1 \) through \( O_4 \).
In Fig. 4, each plotted curve for each radio range $r$ exhibits a similar decrease in $P_{suc}$ although the mean number of vehicles successfully receiving information via IVC is completely different for different radio ranges, $r$. Again, the curves for “original” and those for “estimated” show good agreement.

The sensitivity of the parameter $a$ to $P_{suc}$ under a fixed mean space headway is shown in Fig. 5. The result in Fig. 5 indicates that $P_{suc}$ is a decreasing function of $a$. This is because it is likely that the vehicles in the target range includes both category-1 vehicles and category-2 vehicles for a large $a$. If a vehicle is a category-1 vehicle, the probability that the vehicle fails to receive information via IVC and $P_{suc}$ becomes small. The curve for “original” and that for “estimated” have a small difference but still show good agreement.

The sensitivity of the speed, $v$, of the vehicle to $P_{suc}$ is shown in Fig. 6. The speed $v = 10$ m/s corresponds to driving in an urban area and $v = 30$ m/s corresponds to driving on a highway. $P_{suc}$ for $v = 30$ m/s is lower than that for $v = 10$ m/s. This is because more vehicles can pass the target point within a certain minute at $v = 30$ m/s than at $v = 10$ m/s. To attain the same $P_{suc}$ for $v = 30$ m/s as that for $v = 10$ m/s, the delay, $u$, must be 1/3. This is because $P_{suc}$ is a function of $uv$ and takes the same value for fixed $uv$ even when $v$ varies.
6 Conclusion

This paper evaluated the performance of the combined vehicular communication implemented by IVC and additional communication media. Explicit formulas calculating performance metrics were derived. Through the numerical examples, it was discovered that performance can vary whether the communications are applied to (i) low penetration of IVC or not, (ii) high vehicular density or not, and/or (iii) high speed or not. Thus, to attain a certain level of performance, it was proposed that the information delivery delay of the additional communication should be appropriately designed. The method determining delay based on basic safety information observed through vehicular communication was also proposed.

References