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Accident prevention via information transfer from vehicles to pedestrians based on visual functions of velocity perception

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**Abstract:** To prevent potentially dangerous decisions made by pedestrians while crossing roads, this paper presents an examination of the information that needs to be effectively conveyed from a vehicle to the pedestrians. We studied the information required by the pedestrians to maximize the distance at which they can perceive the velocity of the vehicle, and we examined where to display this information. We used a visual model that is capable of analysing and obtaining the tangential and normal components of vehicle velocity from 2D polar coordinates, with the pedestrian’s eyeball as the origin. In this model, the velocity components contributing to the maximum distance at which the speed is detectable are determined by the pedestrian eye level, overall vehicle height, and perception threshold for each velocity component. It was shown that if the tangential velocity component contributes, displaying the vehicle-location in the visual field by showing the dividing line between the vehicle and the road surface can be useful. If the normal component contributes, it can be effective to display the vehicle’s frontal area by showing the dividing line between the vehicle and the background. These findings can provide the requirements of the effective provision of information that prevents pedestrian accidents.

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Dr. Yasushi Yokoya (born in Tokyo, Japan, in September 1966) received B.S., M.S. and Ph.D. degrees in solid state physics from Tokyo University of Science, Japan, in 1991, 1993 and 1996, respectively. Since 1998–2012, he was a researcher at Japan Automobile Research Institute (JARI). He was engaged in the investigation of driver’s visual field, driving behavior, accident generation mechanisms, driver support technology. Since 2013, he has been an associate professor at the Department of Vehicle and Mechanical Engineering in the Meijo University. His research interests include the following: human machine interface (HMI) between vehicles and passengers, inside vehicles and between vehicles and pedestrians, vehicular traffic flow dynamics and modeling. These research activities become increasingly important as recent popularization of the driver assist systems and the spread of autonomous vehicles in the coming future.

**PUBLIC INTEREST STATEMENT**

We can dodge the ball unconsciously as it come flying towards our head. Avoiding collisions with moving objects is a critically important skill through the senses and motor abilities, which is based on depth and motion perception. The image of the external world on our retina is essentially two-dimensional, and yet it is possible to appreciate its three-dimensional character with remarkable precision, thanks to depth cues. The perception of depth in a two-dimensional pattern depends on a variety of cues: the knowledge of the true shape and size of objects, relative sizes of objects, etc. Unfortunately, these cues are prone to considerable biases in the visual perception in traffic scenes and thus cause failure to estimate distance and speed of approaching vehicles. Our research presents the conditions necessary for effective communication that prevents road traffic participants from making inappropriate decisions from the perspective of visual function.
 Subjects: Transport & Vehicle Engineering; Perception; Visual Perception

Keywords: Pedestrian accident; motion perception; accident statistics; geometrical optics

1. Introduction
The number of road fatalities in Japan in 2020 was reported to be 2,839 people. Compared with 1970, which witnessed 16,765 fatalities, this represents a reduction of more than 80%. When viewed in a global context, alongside the International Traffic Safety Data and Analysis Group (IRTD) member countries, Japan ranked eighth, with 3.3 road fatalities per 100,000 people in 2018. In 2018, Japan ranked 17th, with 5.6 road fatalities occurring in driving distance of one million kilometres. The period between 2010 and 2018 witnessed reductions of 25.6% (17th) and 26.5% (11th) in the rate of road fatalities involving vehicle occupants and pedestrians, respectively, leaving significant room for improvement (Road Safety Annual Report, 2020).

The overall number of road fatal accidents in Japan in 2020 was 2,784. Of these incidents, 34% (942 cases) were pedestrian accidents. Furthermore, 70% (651 cases) of these pedestrian fatalities occurred while the pedestrians were crossing the road. When broken down by road type, 455 cases (making up over 70% of the total) of pedestrian fatalities while crossing the road consist of intersections without signals (187 cases), nearby intersections (79 cases) and non-intersection road (189 cases). This reflects that errors in judgment by pedestrians crossing the road have a close connection with the occurrence of accidents. This is also supported by the fact that around 60% of the pedestrians involved in pedestrian fatalities while crossing the road acted in a way that contravenes the law, i.e. crossing immediately in front or behind a car or crossing at a non-designated pedestrian crossing (National Police Agency, 2020).

There are other characteristics that can be observed based on the width of the road. Japanese road accident statistics classify accidents by road width using 5.5 m as a threshold. Road fatalities are consistently decreasing for roads that are 5.5 m or wider. But no such trend can be observed for roads narrower than 5.5 m. Based on functionality, roads are broadly classified into major roads, which form the skeletal structure of local activity zones and metropolitan zones, and residential roads in residential areas, which are mainly used by local residents. Roads that are under 5.5 m in width fall under the category of residential roads.

Based on this, the government continues to implement road safety measures as part of government/private initiatives. In addition to measures that focus on vehicles, road improvements and road traffic measures from a pedestrian perspective are also advocated, such as a sidewalk widening on residential road. Corrective measures to reduce pedestrian accidents on residential roads that are being implemented include enforcing stronger control through low-speed regulations, improvement in the road environment, installation of LED signal lights and provisioning/widening of pedestrian walkways.

In contrast, vehicle-based measures focusing on automotive manufacturers have also been advocated. These include the necessitation of more sophisticated safety equipment and research on automated driving using artificial intelligence. However, on narrow residential roads, pedestrians and vehicles are in close physical proximity to each other, necessitating vehicle technologies such as accurate pedestrian detection and prediction of complex pedestrian behaviors. Nevertheless, several issues would still exist, even after the realization of these measures.

Recently, European countries have engaged in constructing a variety of road spaces for pedestrians. This includes the safety initiatives predicated on pedestrians and vehicles sharing residential roads. For instance, attempts have been made, with some positive results (Karnadcharuk et al., 2014), to create safe spaces shared by pedestrians and vehicles (Shared Space) by means of road space design, a minimum set of traffic rules and improvement of mutual communication of intent by promoting communication between traffic participants. Since on residential roads pedestrians
and vehicles are in close physical proximity, a failure to uphold safe driving due to human error or pedestrians inappropriately crossing the road are directly linked to pedestrian accidents. Therefore, the active promotion of communication between pedestrians and drivers can lead to a reduction in traffic accidents.

When a pedestrian crosses a road and there is an approaching vehicle, perception and movement act in tandem. This is an essential function for human beings that helps avoid collision with a moving visual object. This function is characterized by the time to collision (TTC) or the time to arrival (TTA), which is based on an estimation of the time remaining before collision or arrival of the visual object. The ratio of the object’s angular size to its rate of looming, which is called tau, is one of the quantities to judge TTC (or TTA) (Lee, 1976). However, the relationship between TTC and movement to avoid collision is dependent on the experimental method used to study it, and it has been highlighted that factors other than the known $\tau$ are involved as well (Lugtigheid & Welchman, 2011). For instance, if the size of the visual object is known, then the looming rare contributes to the decision on movement (López-Moliner et al., 2007). Furthermore, it is not $\tau$ but the distance (Wann, 1996), (Wann et al., 1993), visual information other than $\tau$, that contributes to the timing when the driver of a vehicle starts applying the brakes (Tresilian, 1997), (Tresilian, 1999); this is believed to be a typical example of decision-making through TTC.

There are experimental studies addressing the visual looming of vehicles, which can lead to accidents of pedestrians crossing the road or railway level crossings. Pedestrians identify safe time gaps between approaching vehicles when crossing a road. It has been shown that vehicle approach speed has a substantial influence on the size of chosen gaps, i.e., smaller gaps at higher speed (Oxley et al., 2005), (Lobois & Cavallo, 2007). It was revealed that the effect of speed on gap acceptance depends on accuracy of TTA estimated by pedestrians (Petzoldt, 2014). Other experimental studies on the visual looming are of a so-called size speed bias, which describes the phenomenon that observers underestimate the speed of larger objects, such as aircraft or trains (Clark et al., 2013). Furthermore, it was pointed out discrepancy between the size speed bias and the size arrival effect (size effect on TTA) (Petzoldt, 2016). In these studies, the measured quantities, namely, accepted gaps, estimated TTA and perceived speeds, are based on visual function of observers. To prevent pedestrians from making inappropriate decisions about crossing the road, it is necessary to study the communication between pedestrians and vehicles from the perspective of visual function.

This article examines what constitutes useful information and where it should be displayed. Like vehicles offering pedestrians with visual information to prevent inappropriate road crossing, which is a primary factor in the pedestrian's perspective that leads to accidents. To achieve this, a visual model is built based on visual function using visual information such as depth or distance cues acquired by the pedestrian who wants to cross the road while viewing an approaching vehicle.

The rest of this paper is organized as follows. Section 2 discusses visual information that is used for decision making while crossing the road based on the cases observed in pedestrian accidents. A visual model is demonstrated on this basis. Section 3 outlines the results of a simulation using the visual model. Section 4 discusses, based on the simulation results, what constitutes effective information and where on the vehicle the information should be shown. Section 5 summarizes the results and conclusions and describes scope for further work.

2. Pedestrian visual model

2.1. Scenarios in road crossing leading to pedestrian accidents
We use two types of accident data to discern the relationship between pedestrians and vehicles, in situations where inappropriate decisions are made while crossing the road, one of the primary factors that lead to pedestrian accidents. These are the traffic accident database, hereafter termed
J-TAD (macro), and the traffic accident data, hereafter termed J-TAD (micro), of the Institute for Traffic Accident Research and Data Analysis (ITARDA) (https://www.itarda.or.jp/english/activities).

J-TAD (macro) comprises traffic accident and driver data from the National Police Agency and road and vehicle data from the Ministry of Land, Infrastructure and Transport. The primary feature here is that the database covers all traffic accidents involving fatalities nationwide and thus provides adequate data for statistical analysis.

In contrast, J-TAD (micro) contains data that have been collected by individual ITARDA investigators on traffic accidents that occurred in specific regions, and it comprises detailed analytical results about drivers, roads, traffic environments and vehicles. Compared with J-TAD (macro), the primary feature of J-TAD (micro) is that it enables the analysis of individual accidents.

Analysis of J-TAD (macro) data shows that approximately 80% of the vehicles involved in fatal pedestrian accidents moved forward in a straight line. Moreover, the speed of the vehicle at the time that the driver identified the pedestrian (risk recognition velocity, \( V_r \)) achieved a cumulative ratio of 90% at \( V_r \approx 60 \text{ km/h} \) (Ishikawa, 2010).

A J-TAD (micro) analysis, by contrast, provides the time between the pedestrian starting to cross from the edge of the road (crossing start time, \( T_s \)) and the collision in pedestrian accidents (fatal, serious injury, minor injury) (Ishikawa, 2010). To calculate \( T_s \), the walking speed (1–3 m/s) was used, which was estimated based on pedestrian age. \( T_s \) was examined according to the road-crossing direction of the pedestrians. The cumulative frequency of the number of pedestrian accidents for which \( T_s = 3 \) s when the pedestrian crossed the road on the left hand side from the vehicle’s perspective, was found to be over 70%. In contrast, when crossing on the right hand side from the vehicle’s perspective, the cumulative frequency was less than 50% even if \( T_s = 5 \) s, with the \( T_s \) frequency shifting to higher values. The reason for this is that the pedestrian crossed from the lane opposite to the one containing the vehicle, and therefore, the time until the collision increased. Note that vehicles in Japan are driven on the left hand side of the road. If the road was crossed from the right hand side from the vehicle’s perspective, the presence of any vehicle in the opposite lane affects the decision to cross; hence, this study uses \( T_s \approx 3 \) s, at which several pedestrian accidents occur if the road is crossed from the left hand side, from the vehicle’s perspective. In this case, the distance between the pedestrian and the vehicle at the point that the pedestrian starts crossing is 50 m if vehicle velocity is 60 km/h.

### 2.2. Visual information used in road crossing decisions

The visual perception of distance and velocity uses a variety of qualitatively different visual information, each with their own useful distance regions. Furthermore, the accuracy of this perception is affected by the observer’s knowledge about the size of the visual object and the visual environment (Cutting & Vishton, 1995).

According to accident data, in the circumstances at which many pedestrian accidents occur (crossing from the left hand side from the vehicle’s perspective, at \( T_s = 3 \) s), the distance between the pedestrian and the vehicle at the time the pedestrian starts to cross is 50 m (vehicle velocity \( V = 60 \text{ km/h} \)). Compared to binocular disparity in binocular vision and motion parallax with monocular vision, the position of the vehicle in the field of view and its relative size effectively acts on the perception of distance and velocity at this distance (Nagata, 1984).

For perception that uses the position of the visual object in the field of vision, the distance is obtained based on assumptions that relate to the spatial position of the visual object in the horizontal plane. In this case, the height of the observer at the eye level is used to obtain the distance to the object, by means of the angle of depression relative to the object on the horizontal plane. This perception is not dependent on the size of the visual object (Foley et al., 2004), (Loomis et al., 1992), (Ool et al., 2001). In contrast, for perception that uses the relative size of the visual
object, the distance is obtained through the retinal image corresponding to the angle from the visual object to the eyeball (visual angle) and through size constancy based on knowledge about the actual size of the visual object that is accumulated through experience (Gillam, 1995). In this case, the perception accuracy is dependent on the knowledge about the actual size of the object.

If the visual object moves relative to the observer, this is accompanied by optical flow, which is the movement of the retinal image. Even in the absence of depth cues, spatial structure or movement can be perceived through optical flow alone and therefore, optical flow contributes specifically to monocular vision (Longuet-Higgins & Prazdny, 1980), (WA Warren, 2004).

When a pedestrian sees an approaching vehicle, in the case of perception through the position of a visual object in the field of vision, the velocity is obtained based on a change with time in the retinal image corresponding to the change in the depression angle of a vehicle on the pedestrian's eye level (WH Warren, 1995), (Nakayama & Loomis, 1974). In contrast, in the case of perception that uses the size of a visual object, the velocity is obtained from size constancy based on a change with time in the retinal image (looming rate) corresponding to the expansion of the visual angle to the vehicle and on the knowledge about the actual size of the vehicle (Bex & Makous, 1997), (Orban et al., 1995).

2.3. Visual model for approaching vehicle

In this section, we describe the visual model used for the simulation. We constructed a model based on visual information used in road-crossing decisions, which have been derived from road-crossing scenarios observed in pedestrian accidents. This model is applicable for cases wherein two types of monocular vision are used to perceive the distance and velocity of the approaching vehicle—the location in the field of vision and the relative size of the visual object. This is because, as discussed earlier on the basis of accident data, the vehicle's location in the field of vision and the relative vehicle size through monocular vision work effectively in the perception of the distance of the vehicle and its velocity. Moreover, because J-TAD (macro) analyses show that around 80% of the vehicles involved in fatal pedestrian accidents were moving forward in a straight line (Institute for Traffic Accident Research and Data Analysis (ITARDA), 2012), we assume that the vehicle constituting the visual object also moves forward in a straight line that includes the vehicle itself and the pedestrian.

The geometrical relationship between the retinal image and the distance is shown in Figure 1, using a two-dimensional plane including the pedestrian's median plane and the visual object. The figure demonstrates a situation wherein the point that forms the visual object through eye movement (fixation point) is shown on the fovea of the retina. The nodal point of the fixation point, the lens centre, and the fovea are connected by a single line (visual axis). The coordinates on the retina in relation to the visual object are determined with the fovea as the origin.

The pedestrian stands in a vertical position in relation to the horizontal plane on point O on the ground. Let the distance from point O to visual object A be X, let the height from the horizontal plane to nodal point p be H and let the distance (visual axis length) from nodal point p to the retina be 1. Furthermore, let the angle of the visual axis with the plane parallel to the horizontal plane from nodal point p be ϕ (depression angle). Let the intersection of visual axis and retina be origin O' of the visual axis. The curve enveloping O' is an arc, the radius of which is formed by the visual axis length with nodal point p at its centre. Let this be the effective retina S (hereafter termed retina). When velocity of the visual object is V, velocity v of the retinal image projected on retina S is given by ϕ.

Movement of visual object A in the two-dimensional polar coordinate system with eyeball node point p as origin is expressed by Equations (1) and (2). The symbols r and θ, respectively, adopt the radial direction and anticlockwise rotation as true. Velocity V of visual object is broken down into tangential component V_t and normal component V_n.
The tangential and normal components of velocity $V$ of the visual object are perpendicular and parallel, respectively, to the visual axis. These two components are connected with the two types of visual information used in perceiving velocity, namely, the position of the visual object in the field of vision and the relative size of the visual object, as outlined in the previous section. In perception through the visual object’s location in the field of vision, the velocity $v$ that is projected on the retinal surface $S$ directly corresponds to the tangential component of velocity $V_t$ (Figure 1), and the size of the visual is expressed through angular velocity $\theta$ of the depression angle in relation to the object, as expressed in Equation (4).

$$v = -\frac{d}{dt} \tan^{-1} \frac{H}{r} = \frac{H}{r^2} V$$  \hspace{1cm} (4)
On the other hand, in perception that uses the size of the visual object, velocity \( v \) that is projected on the retinal surface \( S \) is expressed through angular velocity \( \dot{\varphi} \) of visual angle \( \varphi \) to the visual object, through normal component \( V_n \) mediating size constancy. This is described in Figure 2 and Equation (5).

\[
\dot{\varphi} = -\frac{d}{dt} 2 \tan^{-1} \frac{h}{2r} = \frac{h}{(h/2)^2 + r^2} V_n
\]

**2.4. Distance at which velocity becomes detectable**

The maximum distance at which the velocity of an approaching vehicle can be perceived (maximum perceivable distance) is obtained using the perception threshold for each component for vehicle velocity.

In Equation (4), if the value \( \dot{\theta} \) is minimum, namely, the perception threshold \( \dot{\theta}_{th} \), the distance \( X \) becomes maximum for the given values of \( H \) and \( V \). Then the maximum perceivable distance \( X_{nc} \) through the tangential component is obtained from Equation (6). For the normal component, on the other hand, the distance \( X \) given by Equation (5) becomes maximum in a manner similar to that for the tangential component if the value \( \dot{\varphi} \) is minimum, that is, the perception threshold \( \dot{\varphi}_{th} \), for the given values of \( H \), \( V \) and \( h \). Then the maximum perceivable distance \( X_{nc} \) through the normal component is obtained from Equation (7).

\[
\dot{\theta}_{th} = \frac{H}{H^2 + X_{nc}^2} V
\]

\[
\dot{\varphi}_{th} = \frac{h}{(h/2)^2 + X_{nc}^2} \sqrt{H^2 + X_{nc}^2} V
\]

If the existence of the horizontal plane is not taken into consideration in perception through the normal component, as shown in Equation (7), then \( X_{nc} \) is expressed using Equation (8).

\[
\dot{\varphi}_{th} = \frac{h}{(h/2)^2 + X_{nc}^2} V
\]

The perception of a moving visual object is achieved by perceiving the direction of movement and speed. The perception threshold of direction of movement is shown to be virtually equal to the perception threshold for the visual object (Ball et al., 1983). The perception threshold for the visual object is defined by the minimum visual angular separation and is \( 2.9 \times 10^{-4} \text{ rad} \) (10 arcmin) if visual acuity is 1.0 in the Landolt ring test.

The perception threshold for speed is expressed using the angular velocity determined using the displacement of the visual object. The vertical and horizontal directions of displacement vary in relation to the visual axis. For the vertical direction, the perception threshold is expressed through the angular velocity of the displacement of the visual object in relation to the eyeballs; for the horizontal direction, the threshold is expressed through the angular velocity of the visual angle of the visual object size in relation to the eyeballs.

Perception threshold \( \dot{\theta}_c \) in the vertical direction, relative to the visual axis, is expressed through Equation (9) using distance to the visual object \( X \), velocity \( V \) and distance from the visual axis to the visual object \( L \).

\[
\dot{\theta}_c = \frac{L}{L^2 + X^2} V
\]
In contrast, the perception threshold ($\phi_p$) in the horizontal direction in relation to the visual axis is expressed through Equation (10), using with the distance to the visual object ($X$), velocity ($V$) and size of the visual object ($B$).

$$\phi_p = \frac{B}{(B/2)^2 + X^2}V$$

(10)

Furthermore, if the existence of the horizontal plane is disregarded, perception threshold $\phi_{th}$ by Equation (7) in relation to the normal component for velocity is consistent with Equation (10).

3. Simulation

The contribution of the two types of visual information described in the visual model of perception of the velocity of an approaching vehicle are studied by means of a simulation. The risk recognition velocity $V_r$ is used for the vehicle velocity. The simulation is carried out with three different velocities: 60 km/h, for which the cumulative ratio reached 90% in J-TAD (macro), 50 km/h and 70 km/h.

For the perception thresholds of vehicle velocity, we employ, for the tangential velocity component, the threshold for the vertical direction to the visual axis, $\phi_{th_v}$=$8.7 \times 10^{-3}$ rad/s (Lappin et al., 2009), and for the normal velocity component, the threshold for the horizontal direction to the visual axis, $\phi_{th_n}$=$1.17 \times 10^{-2}$ rad/s (Maddox & Kiefer, 2012). Moreover, because the actual gaze time taken by a pedestrian to decide to cross in with an approaching vehicle is unknown, it is set at 1 s.

Figure 3 shows $H$ dependency of maximum perceivable distance $X_{tc}$ expressed through the tangential component of velocity for vehicle velocity $V = 70$ km/h, 60 km/h and 50 km/h, as described in Equation (6). The area above each curve is the distance range where vehicle velocity is undetectable. Using eye-level height $H$ based on average Japanese height that is 90% of overall height (Ministry of Health, Labour and Welfare, 2017), results are, for adult males ($H = 1.54$ m), $X_{tc} = 58.7$ m ($V = 70$ km/h), $X_{tc} = 54.3$ m ($V = 60$ km/h), $X_{tc} = 49.6$ m ($V = 50$ km/h). For adult females and seniors ($H = 1.4$ m), $X_{tc} = 55.9$ m ($V = 70$ km/h), $X_{tc} = 51.8$ m ($V = 60$ km/h), $X_{tc} = 47.3$ m ($V = 50$ km/h). For children ($H = 1.1$ m for 7-year old), $X_{tc} = 49.6$ m ($V = 70$ km/h), $X_{tc} = 45.9$ m ($V = 60$ km/h), $X_{tc} = 41.9$ m ($V = 50$ km/h).

Figure 4 shows $h$ dependency of maximum perceivable distance $X_{nc}$ given by the normal component of velocity, for vehicle velocity $V = 70$ km/h, 60 km/h and 50 km/h, as portrayed in Equation (6). The area above each curve is the distance range where vehicle velocity is undetectable. Based on the vehicle classification used in J-TAD (macro), vehicles used in the simulation were classified into sedans, minivans and large vehicles. For the overall vehicle height $H$, results were as follows: $X_{nc} = 49.9$ m ($V = 70$ km/h), $X_{nc} = 46.2$ m ($V = 60$ km/h), $X_{nc} = 42.1$ m ($V = 50$ km/h) for sedans ($H = 1.5$ m); $X_{nc} = 56.2$ m ($V = 70$ km/h), $X_{nc} = 52.0$ m ($V = 60$ km/h), $X_{nc} = 47.4$ m ($V = 50$ km/h) for minivans ($H = 1.9$ m); and $X_{nc} = 70.6$ m ($V = 70$ km/h), $X_{nc} = 65.3$ m ($V = 60$ km/h), $X_{nc} = 59.6$ m ($V = 50$ km/h) for large vehicles ($H = 3.0$ m). The impact of $H$ on maximum perceivable distance $X_{nc}$ through the normal component for velocity is very small as can be seen from Equation (7).

Maximum distance at which pedestrians last perceive the velocity of a vehicle $X_{pc}$ is expressed in Equation (11) using $X_{tc}$ and $X_{nc}$ which are obtained from both components for velocity.

$$X_{pc} = \max\{X_{tc}, X_{nc}\}$$

(11)

Figure 5 shows the boundary line on the $H$-$h$ plane where the magnitude relation of $X_{tc}$ and $X_{nc}$ which determines $X_{pc}$ turns. The boundary line is expressed through $X_{tc} = X_{nc}$ and the area above and below the boundary line corresponds to $X_{tc} > X_{nc}$ and $X_{tc} < X_{nc}$ respectively. If $X_{nc}$ from
Equation (8), is used when the presence of the horizontal plane is not taken into consideration, the boundary line can be expressed through Equation (12).

\[
h = \frac{2V}{\varphi_{\text{th}}} - 2 \sqrt{\left(\frac{V}{\varphi_{\text{th}}}\right)^2 + H^2 + \frac{V}{\theta_{\text{th}}} H}
\]  

(12)

In the range where eye level height \( H \) and vehicle height \( h \) can be obtained in practice, Equation (12) will be Equation (13) if vehicle velocity \( V \) and the extent of the perception thresholds \( \theta_{\text{th}}, \varphi_{\text{th}} \) for both components are taken into consideration (Lappin et al., 2009), (Maddox & Kiefer, 2012). Here, Equation (14) was used. Equation (13) reproduces Figure 5, obtained through the simulation.

\[
h \approx \frac{\varphi_{\text{th}} H}{\theta_{\text{th}}}
\]  

(13)

\[
\left. \frac{dh}{dH} \right|_{H=0} = \frac{\varphi_{\text{th}}}{\theta_{\text{th}}}
\]  

(14)

Figure 3. \( H \) dependency of \( X_{tc} \) through tangential component of vehicle velocity \( (V = 70, 60, 50 \text{ km/h}) \).

Figure 4. \( H \) dependency of \( X_{nc} \) through normal component of vehicle velocity \( (V = 70, 60, 50 \text{ km/h}) \).
The velocity components providing $X_{pc}$ can be determined through Equations (15) and (16), using Equation (13).

$$\frac{h}{H} < \frac{\psi_{th}}{\phi_{th}} \text{ then } X_{pc} = X_{tc} \quad (15)$$

$$\frac{h}{H} > \frac{\psi_{th}}{\phi_{th}} \text{ then } X_{pc} = X_{nc} \quad (16)$$

When eye level height $H$, vehicle velocity $V$ and extent of perception thresholds $\phi_{th}, \psi_{th}$ for each component are taken into consideration, the impact of vehicle velocity on the location of the boundary line on the $H$-$h$ plane can be disregarded, as supported by Equation (17).

$$\frac{\partial h}{\partial V} = \frac{2V/\psi_{th}^2 - H/\phi_{th}}{\sqrt{V^2/\psi_{th}^2 + H^2 - HV/\phi_{th}}} \approx 0 \quad (17)$$

4. Discussion
We will now compare the results of the simulation using the visual model with the time that the pedestrians involved in accidents started crossing. We will also discuss the content of effective information provision as well as the location where this information may be presented on the vehicle. The time that road crossing started referred to here is expressed by the time to collision from the point that the pedestrian starts crossing from the edge of the road. This TTC is obtained from accident data.

4.1. Detectable/non-detectable velocity and road crossing timing
When using eye level height $H$ based on average Japanese height, the distribution of maximum perceivable distance $X_{tc}$ through the tangential component of vehicle velocity is as follows; for adult males from $X_{tc} = 58.7$ m ($V = 70$ km/h) to $X_{tc} = 49.6$ m ($V = 50$ km/h), for adult females and seniors from $X_{tc} = 55.9$ m ($V = 70$ km/h) to $X_{tc} = 47.3$ m ($V = 50$ km/h) and for children from $X_{tc} = 49.6$ m ($V = 70$ km/h) to $X_{tc} = 41.9$ m ($V = 50$ km/h). Refer Figure 3.

On the other hand, using vehicle height $h$ of sedans, minivans and large vehicles based on the vehicle classification used in J-TAD (macro), the distribution of maximum perceivable distance $X_{nc}$ through the normal component of vehicle velocity is as follows: for sedans, from $X_{nc} = 49.9$ m ($V = 70$ km/h) to $X_{nc} = 42.1$ m ($V = 50$ km/h), for minivans from $X_{nc} = 56.2$ m ($V = 70$ km/h) to $X_{nc} = 49.3$ m ($V = 50$ km/h). Refer Figure 3.
= 47.4 m (V = 50 km/h), for large vehicles from $X_{nc} = 70.6$ m ($V = 70$ km/h) to $X_{nc} = 59.6$ m ($V = 50$ km/h). Refer Figure 4.

If, at the time that a pedestrian starts crossing the road, maximum perceivable distance $X_{pc}$ exceeds the distance between pedestrian and vehicle, then the pedestrian is able to perceive vehicle velocity at that point in time. When using crossing start time $T_s = 3$ s, at which many pedestrian accidents occur when crossing the road from the left hand side from the vehicle’s perspective, the distance between the vehicle and pedestrian at the point that the pedestrian starts crossing the road is $X = 58.3$ m ($V = 70$ km/h), $X = 50.0$ m ($V = 60$ km/h) and $X = 41.7$ m ($V = 50$ km/h). This means that the distance between the vehicle and pedestrian at the point that most pedestrians who are involved in accidents start crossing the road is in the boundary area where vehicle velocity is detectable or undetectable. Accordingly, the simulation using the visual model as proposed in the present paper is useful as a means to clarify the role played by visual properties relating to vehicle movement, in relation to inappropriate road crossing decisions made by pedestrians that lead to accidents.

4.2. Visual information contributing to perception of velocity
Simulation results showed that maximum perceivable distance $X_{pc}$ changes depending on pedestrian eye level $H$, size (overall height) of the vehicle $h$ and vehicle velocity $V$. We consider the two types of visual information relating to perception of vehicle velocity, at the point of time that pedestrians involved in accidents start crossing the road. Using average Japanese height, eye level height $H$ is set at 90% of overall height. Overall vehicle height $h$ is based on the vehicle classification in J-TAD (macro) (sedan, minivan, large vehicle). For vehicle velocity $V$, we use three velocities, 60 km/h (cumulative ratio of risk recognition velocity $V_r$) calculated based on J-TAD (macro), 50 km/h and 70 km/h. Moreover, we used crossing start time $T_s = 3$ s, which is associated with a high frequency of pedestrian accidents and which is derived from J-TAD (micro), for the time that pedestrians start crossing the road.

If the vehicle is a sedan ($h = 1.5$ m), vehicle velocity $V = 70–50$ km/h and crossing start time $T_s = 3$ s, it is detectable for adult males ($H = 1.54$ m) with maximum perceivable velocity, based on Equation (11), at $X_{pc} = X_{tc} = 58.7$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 54.3$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 49.6$ m ($V = 50$ km/h). However, perception of $V = 70$ km/h is near the limit. For adult females/seniors ($H = 1.4$ m), maximum perceivable distance is $X_{pc} = X_{tc} = 55.9$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 51.8$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 47.3$ m ($V = 50$ km/h), and although $V = 60–50$ km/h is detectable, perception of $V = 60$ km/h is near the limit and $V = 70$ km/h is undetectable. For children ($H = 1.1$ m), maximum perceivable distance is $X_{pc} = X_{tc} = 49.9$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 46.2$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 42.1$ m ($V = 50$ km/h), with perception of $V = 50$ km/h near the limit and $V = 70–60$ km/h undetectable.

If the approaching vehicle is a minivan ($h = 1.9$ m), maximum perceivable distance for adult males is $X_{pc} = X_{tc} = 58.7$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 54.3$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 49.6$ m ($V = 50$ km/h), with $V = 70–50$ km/h detectable but perception of $V = 70$ km/h near the limit. For adult females/seniors and children alike, maximum perceivable distance is $X_{pc} = X_{tc} = 56.2$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 52.0$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 47.4$ m ($V = 50$ km/h), with $V = 60–50$ km/h detectable but perception of $V = 60$ km/h near the limit and with $V = 70$ km/h undetectable.

If the approaching vehicle is a large vehicle ($h = 3.0$ m), maximum perceivable distance for adult males, females/seniors and children is $X_{pc} = X_{tc} = 70.6$ m ($V = 70$ km/h), $X_{pc} = X_{tc} = 65.4$ m ($V = 60$ km/h) and $X_{pc} = X_{tc} = 59.6$ m ($V = 50$ km/h), with $V = 70–50$ km/h detectable.

Figure 6 shows the boundary lines for the two types of velocity components, providing the maximum distance $X_{pc}$ at which a pedestrian is able to perceive the velocity of an approaching vehicle as well as the eye level height of pedestrians and vehicle height, on a $H$-$h$ plane. Figure 6
(a)–(c) correspond to when vehicle velocity is \( V = 70, 60, 50 \) km/h. Figure 6 (a)–(c) also shows the areas where velocity is undetectable at the point when the pedestrian saw the approaching vehicle from the edge of the road three seconds prior to the collision. The area where velocity of the approaching vehicle is undetectable at crossing start time \( T_s = 3 \) s is obtained through Equation 6 and Equation 7, with \( H \leq 1.52 \) m and \( h \leq 2.03 \) m \( (V = 70 \text{ km/h}) \), \( H \leq 1.31 \) m and \( h \leq 1.76 \) m \( (V = 60 \text{ km/h}) \), \( H \leq 1.09 \) m and \( h \leq 1.46 \) m \( (V = 50 \text{ km/h}) \).

The contribution of the tangential and normal components in maximum distance at which a pedestrian is able to last perceive velocity of an approaching vehicle is determined through Equation 15 and Equation 16. In the case of adult males \( (H = 1.54 \text{ m}) \) looking at a vehicle, the tangential component of velocity contributes for sedans \( (h = 1.5 \text{ m}) \) and minivans \( (h = 1.9 \text{ m}) \) through Equation 15, and the normal component of velocity contributes for large vehicles \( (h = 3.0 \text{ m}) \) through Equation 16.
When adult females/seniors ($H = 1.4$ m) look at a vehicle, the tangential velocity component contributes for sedans ($h = 1.5$ m), according to Equation (15), and the normal component contributes for large vehicles ($h = 3.0$ m), according to Equation (16). As the height of a minivan ($h = 1.9$ m) is close to that of the boundary line, both components potentially contribute.

When children ($H = 1.1$ m for a seven-year-olds) look at a vehicle, the normal component of velocity contributes for minivans ($h = 1.9$ m) and large vehicles ($h = 3.0$ m) through Equation (16). Since sedan height ($h = 1.5$ m) is located near the boundary line, both components potentially contribute.

Table 1 shows the velocity components providing maximum perceivable distance $X_{pc}$ in relation to an approaching vehicle at velocity $V = 60$ km/h, in combination with pedestrian eye level height $H$ and vehicle height $h$.

|                  | Children            | Female & Senior      | Male                  |
|------------------|---------------------|----------------------|-----------------------|
| Sedan            | Imperceptible       | Perception via $X_{nc}$ (near the perception limit) | Perception via $X_{nc}$ |
| Minivan          | Perception via $X_{nc}$ (near the perception limit) | Perception via $X_{nc}$ and/or $X_{cc}$ (near the perception limit) | Perception via $X_{nc}$ |
| Large vehicle    | Perception via $X_{nc}$ | Perception via $X_{nc}$ | Perception via $X_{nc}$ |

4.3. Consistency with visual perception in real traffic scenes

In the velocity perception, the contribution of the normal component of the vehicle velocity, namely, the looming rate increases with increasing vehicle height compared with the driver’s eye level height. For large vehicles such as large trucks and buses with a height of close to 4 meters, the normal component of the velocity plays the dominant role in all of the pedestrian eye height (Figure 6). As previously stated, precision of the perception through the normal component mediating size constancy depends on the accuracy of empirically obtained size about the perceived object. In this perception, therefore, pedestrians potentially underestimate (overestimate) the vehicle velocity when they underestimate (overestimate) the vehicle size with the same angular size at the eyeballs. For smaller vehicles such as a sedan with a height of around 1.5 meters, on the other hand, the tangential component of the velocity comes to play the dominant role without children. Since the perception through the tangential component employs the height of the observer’s eyes only, the object size is not related to the precision of perception. It has been suggested that a potential explanation for traffic accidents of large vehicles such as aircraft or trains lie in a so-called size speed bias, which describes the phenomenon that observers underestimate the speed of larger objects. There is some experimental evidence that the size speed bias indeed exists (Petzoldt, 2014), (Clark et al., 2013), (Petzoldt, 2016). Furthermore, it has been shown that this under-estimation might be caused by the observer’s visual focus on a position closer to the centre of the objects, rather than the front (Clark et al., 2016). These experimental findings strengthen the validity of our visual model.

4.4. Effective information content its location on the vehicle

In this section, we use the results obtained through the simulation of distance at which velocity is detectable to obtain the content of effective information provision by the vehicle to the pedestrian, and the location where this information will be presented on the vehicle.

As previously demonstrated, maximum distance $X_{pc}$ at which a pedestrian is able to last perceive the velocity of an approaching vehicle is determined by that visual information out of the two
types of visual information that provides the higher velocity \( v \) of the retinal image compared to the perception threshold for the corresponding velocity components. The retinal image velocity \( v \) is dependent on pedestrian eye level height and the height of the approaching vehicle, and it varies depending on how they combine, Equations (4) and (5). Moreover, the amount of change in the retinal image is proportionate to gaze time. Accordingly, the provision of information that uses the velocity components giving \( x_{pc} \) by a vehicle to a pedestrian enables the pedestrian to perceive the velocity of an approaching vehicle from a larger distance and in a shorter time.

If height \( h \) of the vehicle and eye level height \( H \) of the pedestrian seeing the vehicle satisfy Equation (15), \( x_{pc} \) is provided by the tangential component of velocity. Since the angle of depression in relation to the vehicle on the horizontal plane is used in perception through the tangential component, information showing the location of the vehicle in the field of vision is effective. The area to present this information must be the lower front part of the vehicle to clearly indicate the dividing line between the vehicle and the road surface.

If height \( h \) of the vehicle and eye level height \( H \) of the pedestrian seeing the vehicle satisfy Equation (16), \( x_{pc} \) is provided by the normal component of velocity. Since the visual angle in relation to the vehicle front is used in perception through the normal component, information expressing the size of the vehicle including vehicle height and width is effective. The area to present this information must be the front contours of the vehicle to clearly indicate the dividing line between the front of the vehicle and the background.

Where the combination of vehicle height \( h \) and pedestrian eye level height \( H \) are positioned near the boundary line on the \( H-h \) plane (child vs sedan, adult female/senior vs minivan), both components contribute equally to perception of velocity. In this case, both information on the position of the vehicle in the field of vision and on the size of the vehicle can potentially be used. Information must be presented on the lower part and on the front contours of the vehicle.

Where velocity of an approaching vehicle is undetectable, adult female/senior/child vs sedan/minivan \((V = 70 \text{ km/h})\), child vs sedan \((V = 60 \text{ km/h})\), other, separate means are required to increase gaze time and gaze frequency for the vehicle, in order to ensure adequate amounts of change in the retinal image.

5. Conclusion
This study used a simulation based on a visual model to examine the information that can be effectively conveyed from vehicle to pedestrians, as well as the location where it can be presented. When providing visual information of the velocity of a vehicle traveling towards a pedestrian, it can prevent pedestrians from making inappropriate decisions about crossing the road, which is found to be one of the main causes of pedestrian-based accidents.

In the visual model, the retinal image corresponding to the vehicle velocity is divided into a tangential and a normal component, using 2D polar coordinates with the pedestrian’s eyeball as origin. These components correspond to the two types of information that contribute to the perception of vehicle velocity. That is, the amount of change in the retinal image expressed through the angular velocity of the angle of depression in relation to the vehicle, and the amount of change in the retinal image expressed through the angular velocity of the visual angle to the vehicle. The maximum distance where a pedestrian is last able to perceive velocity of an approaching vehicle is provided by visual information, for which the amount of change in the retinal image per unit time is higher than the perception threshold of the corresponding velocity component of the two types of visual information.

Through a simulation using a visual model, we demonstrated the dependency on the contribution of each component, pedestrian eye level height, vehicle height and vehicle velocity in determining the distance at which vehicle velocity becomes detectable. Through this, we determined
what information is required and where it must be presented to enable a pedestrian to perceive vehicle velocity at a larger distance and in a shorter time in relation to road crossing timing. Road crossing timing here is expressed by the time to collision from the point that the pedestrian starts crossing the road from the edge of the road. This TTC is derived from accident data.

If \( h/H < \phi_{th}/\theta_{th} \) is satisfied when a pedestrian of eye level height \( H \), who intends to cross the road, sees an approaching vehicle of vehicle height \( h \), then the maximum distance at which vehicle velocity is detectable is provided by the tangential component of velocity \( \bar{v}_{th} \). \( \phi_{th} \) expresses the perception threshold for the tangential and normal components of vehicle velocity. Since in perception through the tangential component the angle of depression in relation to the vehicle on the horizontal plane is used, information indicating the position of the vehicle in the field of vision is effective. In terms of where the information is presented, this must be the lower front of the vehicle, in order to clearly indicate the dividing line between the vehicle and the road surface.

In contrast, if \( h/H > \phi_{th}/\theta_{th} \) is satisfied, then the maximum distance at which vehicle velocity is detectable is provided by the normal component of velocity. Since in perception through the normal component the visual angle to the vehicle front is used, information expressing the size of the vehicle front including height and width is effective. In terms of where the information is presented, this must be on the contours of the vehicle front, in order to clearly indicate the dividing line between the vehicle front and the background.

If the combination of vehicle height \( h \) and pedestrian eye level height \( H \) is near the boundary line \( (h/H \sim \phi_{th}/\theta_{th}) \), then both components contribute equally to the perception of velocity. This situation occurs when children see a sedan or adult females/seniors see a minivan. In this case, it is possible to use both information on the position of the vehicle in the field of vision and information on the size of the vehicle front. The information must be presented both in the lower part of the vehicle and contours of the vehicle front.

In cases where the velocity of an approaching vehicle is undetectable, that is, the maximum perceivable distance \( X_{sc} \) is lower than the distance between the pedestrian and the vehicle at the time at which the pedestrian starts to cross the road, a different means is required to increase the gaze time and gaze frequency to the vehicle to ensure adequate amounts of change in the retinal image. This situation occurs when adult females/seniors/children see a sedan/minivan approaching at velocity \( V = 70 \text{ km/h} \) and when children look at a sedan approaching at velocity \( V = 60 \text{ km/h} \).

The perception threshold for velocity depends on the homogeneity and brightness contrast inside the field of vision and on gaze time and visual feature of objects and on the environment these are placed on (Sato, 1998). Therefore, to apply the results obtained in this study to actual road crossing scenarios, the impact of traffic congestion, presence or absence of roadside structures (buildings, trees, guard rails, signs, lights etc.), differences in weather conditions and daylight levels, viewing time etc. also needs to be studied.

Existing technology relating to information provision from vehicles to other vehicles or pedestrians includes daytime running lamps (DLRs). As DLRs increase vehicle visibility, they continue to become more widespread as a means to prevent traffic accidents. The findings presented in this paper on vehicles providing pedestrians with visual information are believed to not only provide new criteria to assess the technology mentioned above from a new perspective but also contribute to improve the functionality of other visual information and presentation techniques, including displays using figures or symbols.

The visual model as proposed in the present paper can be useful to prevent a “right-turn accident” (vehicles in Japan are driven on the left hand side of the road), in which failure to
estimate time gaps or TTA lead to crashes between approaching vehicles. The right-turn accidents account for 13.8% (135 cases) of the total number of fatal accidents of vehicle-to-vehicle in Japan in 2020, which is the third biggest factor behind the crossing collision (346 cases) and the head-on collision (218 cases) (National Police Agency, 2020). To prevent drivers from making inappropriate decisions of turning, the content of effective information provision as well as the location where this information may be presented should be different in different combinations of the driver’s eye level height and the approaching vehicle height.

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