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Association of Impact Velocity with Serious-Injury and Fatality Risks to Cyclists in Commercial Truck–Cyclist Accidents

Yasuhiro Matsui
National Traffic Safety and Environment Laboratory, Japan

Shoko Oikawa
Tokyo Metropolitan University, Japan

Kazuhiro Sorimachi, Akira Imanishi and Takeshi Fujimura
Isuzu Advanced Engineering Center, Ltd., Japan

ABSTRACT – This study aimed to clarify the relationship between truck–cyclist collision impact velocity and the serious-injury and fatality risks to cyclists, and to investigate the effects of road type and driving scenario on the frequency of cyclist fatalities due to collisions with vehicles. We used micro and macro truck–cyclist collision data from the Japanese Institute for Traffic Accident Research and Data Analysis (ITARDA) database. We classified vehicle type into five categories: heavy-duty trucks (gross vehicle weight [GVW] ≥11 × 10^3 kg [11 tons (t)], medium-duty trucks (5 × 10^3 kg [5 t] ≤ GVW < 11 × 10^3 kg [11 t]), light-duty trucks (GVW <5 × 10^3 kg [5 t]), box vans, and sedans. The fatality risk was ≤5% for light-duty trucks, box vans, and sedans at impact velocities ≤40 km/h and for medium-duty trucks at impact velocities ≤30 km/h. The fatality risk was 6% for heavy-duty trucks at impact velocities ≤10 km/h. Thus, the fatality risk appears strongly associated with vehicle class and impact velocity. The results revealed that a 10 km/h reduction in impact velocities could mitigate the severity of cyclist injuries at impact velocities ≥30 km/h for all five vehicle types. The frequency of cyclist fatalities at intersections with traffic signals involving heavy-duty trucks was significantly higher during daytime than that at nighttime. Fatalities involving vehicles making a left turn generally increased with vehicle weight. The frequency of cyclist fatalities involving vehicles making a left turn was the largest for heavy-duty trucks both during daytime (67.6%) and at nighttime (52.3%).

KEYWORDS – commercial truck, collision mitigation system (CMS), vehicle impact velocity, vehicle–cyclist collisions, fatality risk, serious-injury risk

INTRODUCTION

The number of traffic deaths in Japan has decreased during the past 20 years, from 9,943 in 1996 to 3,904 in 2016 (ITARDA 2017). The Japanese government has set a goal of reducing the annual number of fatalities to fewer than 2,500 by 2020 (Japan Cabinet Office 2016). In total, 48% of total traffic deaths in 2016 were among vulnerable road users, such as pedestrians (1,361) and cyclists (509). Vulnerable road user protection is a key countermeasure to reduce casualties in traffic accidents. The Japanese government has implemented various measures to reduce pedestrian deaths, including assessing the safety performance of car hood tops since 2005 (Matsui 2011). This pedestrian head protection regulation in Japan in 2005 is considered to have had a significant role in reducing fatal head injuries (Matsui et al. 2013b). However, no safety regulations have been introduced for vehicle designs to reduce cyclist fatalities in Japan.

Impact velocity is likely to be one of major factors affecting injury severity and mortality of cyclists (Matsui and Oikawa 2015). Active safety devices, such as collision mitigation systems (CMSs) that use sensors for obstacle detection are effective in reducing impact velocities. These devices have great potential in reducing the severity of cyclist injuries and the number of fatalities.

Address correspondence to Prof. Dr. Yasuhiro Matsui, National Traffic Safety and Environment Laboratory, Chofu city, Tokyo, 182-0012, Japan. Electronic mail: ymatsui@ntsel.go.jp

The potential for CMSs to mitigate serious pedestrian injuries and fatalities has been analyzed. Matsui et al. investigated the relationship between car impact velocity and serious-injury and fatality risks to pedestrians using a finite-element model (Matsui et al. 2011). In that study, the pedestrian model was impacted by the center of the front end of a car model. In real-world pedestrian accidents, pedestrians' heads are likely to impact not only the center part but also the side components of the vehicle structure, with the side structure being stiffer than the center (Matsui 2004). The relationship between car velocity and serious-injury and fatality risks to pedestrians has been developed from real-world accident data and reported in various studies (Anderson et al. 1997, Davis 2001, Oh et al. 2008a, 2008b, Rosen and Sander 2009, Kong and Yang 2010, Matsui et al. (2013a)). Matsui et al. (2016a) investigated the relationship between commercial truck velocity and the serious-injury and fatality risks to pedestrians and found that the fatality risks are strongly associated with impact velocity and vehicle class.

Many previously published studies have investigated features of cyclist injuries (Attewell et al. 2001, Hagel et al. 2015, Heesch et al. 2011, Otte et al. 2012, Scheiman et al. 2010, Scholten et al. 2015). Vehicles are regarded to be the largest group of accident opponents of cyclists (Badea-Romero et. al. 2013, Oikawa et al. 2016, Otte et al. 2012). Among different types of vehicle, passenger cars are frequent collision partners in cyclist accidents (Badea-Romero et al. 2013). However, there have been few published papers on the relationship between car impact velocity and injury risk to cyclists. Matsui and Oikawa (2015) researched the relationship between vehicle impact velocity and the serious-injury and fatality risks to cyclists for several types of vehicle—sedans, minivans, box vans, light passenger cars, and light cargo vans.

To reduce cyclist fatalities, it is considered essential to protect cyclists in truck–cyclist collisions. In Japan, CMS-equipped trucks are designed to detect moving vehicles ahead to avoid truck–vehicle rear-end collisions. In the near future, improvements to truck CMSs are expected, to allow detection of vulnerable road users, such as pedestrians and cyclists. The purpose of the present study is to clarify the relationship between truck-impact velocity and the serious-injury and fatality risks to cyclists by using the data from real-world vehicle–cyclist collisions. The relationship between vehicle travel velocity and impact velocity in vehicle–cyclist collisions was investigated using the Japanese Institute for Traffic Accident Research and Data Analysis (ITARDA) database in Japan. The secondary purpose of the present study is to investigate the effect of the road type and driving scenario on the frequency of cyclist fatalities due to collisions with the five vehicle types to clarify the features of traffic accidents involving commercial vehicles.

METHODS

The ITARDA database contains two types of data: macro nationwide (MACRO) and micro in-depth (MICRO) data.

The MACRO data consist of information related to traffic accidents occurring across Japan. The information includes vehicle types, vehicle travel velocities, and cyclist injury severity levels, defined as minor injuries, serious injuries, or fatalities. In the ITARDA database, minor injuries are those requiring less than 1 month for full recovery; serious injuries are those requiring at least 1 month for full recovery; and fatalities are those who died within 24 hours, according to assessments made by doctors when crash victims are taken to hospitals (ITARDA, 2017). When traffic accidents occur, Japanese police officers investigate and record all related information, which is then entered into the ITARDA database. In the MACRO data, vehicle velocity is rounded off in multiples of 10 km/h; for example, 15–24 km/h is coded as 20 km/h. The MACRO data include vehicle travel velocity but not vehicle impact velocity. Vehicle travel velocity is computed from skid mark length. For trucks with gross vehicle weight (GVW) $\geq 8 \times 10^3$ kg (8 t), vehicle travel velocity is calculated both from skid mark length and tachograph data. Japanese vehicle safety regulations have required the installation of analog tachographs, which record travel velocity using a recording disk, for such trucks since 1967. Since 1998, the installation of digital tachographs using memory cards has been required. Thus, tachograph data are used to calculate travel velocities of trucks.

The MACRO data also include information on road type, driving scenario (i.e., start moving, travel straight ahead, right turn and left turn) and time of day of traffic accidents. The MACRO data for vehicle–cyclist accidents for the years 2000–2014 were used in this study.

The MICRO data consist of information related to traffic accidents in specific areas of Japan's Ibaraki Prefecture, and are more detailed than in the MACRO data. Police officers record general information pertaining to accidents, just as in other MACRO cases. Then, ITARDA accident investigators investigate the cases in detail. Both datasets are then transferred into the MICRO database. In the MICRO data, vehicle velocities are coded in increments of 5 km/h, (e.g., 5 km/h, 10 km/h, or 15 km/h). As in the MACRO data, vehicle travel velocity is computed from skid mark length. For trucks with GVW ≥8 t, vehicle travel velocity is calculated both from skid mark length and tachograph data. Vehicle impact velocity is computed from skid mark length and cyclist flight distance. The MICRO data from cyclist accidents that occurred during 1993–2014 were used in this study.

Five types of vehicle involved in vehicle–cyclist collisions were selected in this study. The five vehicle types analyzed were: (a) heavy-duty trucks with GVW ≥11 tons (t), (b) medium-duty trucks 5 t ≤ GVW < 11 t, (c) light-duty trucks <5 t GVW, (d) box vans <3 t GVW, and (e) sedans. Box vans have no hood, and the engines are installed beneath the cabin, excluding light cargo vans categorized as box vans with engine displacement ≤660 cc. Sedans excluded light passenger cars with engine displacement ≤660 cc. The vehicle types analyzed included sedans only for comparison purposes. In this study, the effects of vehicle weight and impact velocity on serious-injury and fatality risks to cyclists were investigated using Analyses 1–3, to be described in the following sections. The effects of road types and driving scenarios on cyclist fatalities due to collisions with the five vehicle types were investigated using Analysis 4.

Analysis 1 (MACRO data)

Using the MACRO data, the number and distribution of minor and serious injuries and fatalities were investigated at different vehicle travel velocities. The travel velocities were categorized into three ranges; ≤30 km/h, 31–60 km/h, and >60 km/h. The differences in serious-injury and fatality risks between commercial trucks and sedans were investigated at these travel velocities.

Using the MACRO data, the serious-injury and fatality risks to cyclists were calculated in increments of 10 km/h for all vehicle types. The risks were calculated at each velocity using the following equations:

$$\text{Serious injury risk (\%)} = \frac{\text{Number of seriously injured cyclists}}{\text{Total number of slightly and seriously injured cyclists}} \times 100 \quad (1)$$

$$\text{Fatality risk (\%)} = \frac{\text{Number of fatal cyclists}}{\text{Total number of slightly and seriously injured and fatal cyclists}} \times 100 \quad (2)$$

Analysis 2 (MICRO data)

Using the MICRO data, relationships between impact velocity and travel velocity for commercial trucks and sedans were developed for minor and serious injuries and for fatalities. For commercial trucks, the MICRO data include heavy-duty, medium-duty, and light-duty trucks and box vans, but the number for each type of commercial truck was insufficient for this type of analysis. Therefore, data were combined for all commercial trucks.

A linear regression equation (y = a × x, where y and x are impact and travel velocity, respectively) was used to express the relationship in the data, where the y-intercept was defined as zero. The relationships between the travel velocity and impact velocity of commercial trucks and sedans were analyzed to identify the linear regression coefficients (a) in the above formula. Statistically significant differences in linear regression coefficients were investigated between minor and serious injuries and between serious injuries and fatalities.

Analysis 3 (MACRO data)

The linear regression formula from Analysis 2 for the relationship between the travel velocity and impact velocity of commercial trucks was applied to the travel velocities from Analysis 1 to obtain impact velocities for heavy-duty trucks, medium-duty trucks, light-duty trucks, and box vans. The linear regression formula from Analysis 2 for the relationship between travel velocity and impact velocity of sedans was applied to the travel velocities from Analysis 1 to obtain impact velocities for sedans. The serious-injury and fatality risks to cyclists were determined for vehicle impact velocities in 10 km/h increments for the five types of vehicle.

Analysis 4 (MACRO data)

To investigate traffic situations in which cyclists were involved in fatal accidents, we focused on the differences in fatality risk to cyclists between daytime and nighttime across the five vehicle types during 2000–2014. ITARDA defines daytime as sunrise–sunset, employing local daily sunrise and sunset times for each prefecture from the Japanese Chronological Science Tables (National Astronomical Observatory of Japan 2016).

The effects of road type on the frequency of cyclist fatalities were investigated using the ITARDA MACRO data. The MACRO data include a category for road type (i.e., intersection with traffic signal, intersection without traffic signal, near intersection, or straight road) where the cyclist accidents occurred. For intersections with crosswalks, 'near intersection' is defined as within 30 m of the painted crosswalk's outer line. For intersections without crosswalks, it is within 30 m from the corner of the intersection.

We also investigated the effects of driving scenario on the frequency of cyclist fatalities. The MACRO data include a category for driving scenario (i.e., start moving, travel straight ahead, right turn, and left turn) when the cyclist accidents occurred.

RESULTS

Analysis 1 (MACRO data)

In 2000–2014, there were 6,553 cyclist fatalities due to collisions with the five vehicle types in Japan. Of these collisions resulting in cyclist fatalities, 17% (1,145) were with heavy-duty trucks, in 15% (991) were with medium-duty trucks, 12% (787) were with light-duty trucks, 10% (649) were with box vans, and 45% (2,981) were with sedans. Table 1 shows the numbers of minor and serious injuries among cyclists, and the serious-injury risk, at vehicle travel velocities of ≤30 km/h, 31–60 km/h, and >60 km/h. The number of cyclists who sustained minor and serious injuries decreased with increasing vehicle weight at ≤30 km/h and 31–60 km/h. The serious-injury risk increased with vehicle weight for all vehicle categories at each velocity.

Table 2 shows significant differences in serious-injury risk between commercial truck types and sedans. At vehicle travel velocities ≤30 km/h and 31–60 km/h, the serious-injury risk to cyclists was significantly higher for all commercial truck types than that for sedans. At >60 km/h, the serious-injury risk to cyclists for heavy-duty and medium-duty trucks was significantly higher than that for sedans.

Table 3 shows the numbers of injuries and fatalities and the fatality risks to cyclists at vehicle travel velocities of ≤30 km/h, 31–60 km/h, and >60 km/h. At vehicle travel velocities ≤30 km/h, although heavy-duty trucks were involved in the fewest collisions with cyclists, they resulted in the most cyclist fatalities. At vehicle travel velocities 31–60 km/h and >60 km/h, cyclist collisions involving sedans resulted in the most cyclist fatalities. Fatality risks increased with vehicle weight at ≤30 km/h and 31–60 km/h. At >60 km/h, the fatality risks to cyclists impacted by medium-duty and heavy-duty trucks were larger than those for light-duty trucks, box vans and sedans.

Table 4 shows the differences in fatality risks to cyclists between commercial trucks and sedans. At vehicle travel velocities ≤30 km/h and 31–60 km/h, fatality risks to cyclists for all commercial truck types were significantly higher than those for sedans. Especially at ≤30 km/h and 31–60 km/h, higher vehicle weight increased the fatality risk to cyclists.

Tables 5 and 6 show the differences in serious-injury and fatality risks to cyclists between different vehicle travel velocities. The serious-injury and fatality risks to cyclists were significantly greater at higher travel velocities than those at lower velocities for each vehicle type.

Because the serious-injury and fatality risks to cyclists are influenced by both vehicle weight and velocity, it is necessary to derive the relationship between the serious-injury and fatality risks to cyclists and vehicle travel velocities for each vehicle type.

Table 7 shows the number of cyclists with minor and serious injuries, and fatalities for the five vehicle types. The serious-injury and fatality risks to cyclists for every additional 10 km/h of impact velocity are shown in Figure 1. The serious-injury and fatality risks increased with vehicle travel velocity (Fig. 1 (a)). In particular, the serious-injury risk for heavy-duty trucks was greater than that for other vehicle types at all vehicle travel velocities. The serious-injury risk was similar among light-duty trucks, box vans, and sedans for all vehicle travel velocities. The fatality risk for heavy-duty trucks was greater than that for other vehicle types at impact velocities ≤30 km/h (Fig. 1 (b)). The fatality risk was similar among heavy-duty and medium-duty trucks at 40–60 km/h. At >70 km/h, the fatality risk in collisions of medium-duty trucks was greater than those by the other vehicle types. The fatality risk was similar among light-duty trucks, box vans, and sedans for all vehicle travel velocities.

Table 1 Cyclist injuries and serious-injury risk to cyclists at different vehicle travel velocities

Vehicle travel velocity	Vehicle type	Minor injury (a) (n)	Serious injury (b) (n)	(a) + (b) (n)	Serious-injury risk (b) /{(a) + (b)} (%)
≤30 km/h	Heavy-duty truck	7,252	1,783	9,035	19.7
	Medium-duty truck	23,522	2,516	26,038	9.7
	Light-duty truck	68,079	4,529	72,608	6.2
	Box van	85,598	5,381	90,979	5.9
	Sedan	751,809	39,283	791,092	5.0
31 km/h–60 km/h	Heavy-duty truck	1,452	808	2,260	35.8
	Medium-duty truck	3,219	1,470	4,689	31.3
	Light-duty truck	7,035	2,140	9,175	23.3
	Box van	7,400	2,076	9,476	21.9
	Sedan	62,480	15,720	78,200	20.1
>60 km/h	Heavy-duty truck	84	146	230	63.5
	Medium-duty truck	84	103	187	55.1
	Light-duty truck	183	121	304	39.8
	Box van	110	59	169	34.9
	Sedan	1,499	991	2,490	39.8
Total	Heavy-duty truck	8,788	2,737	11,525	23.7
	Medium-duty truck	26,825	4,089	30,914	13.2
	Light-duty truck	75,297	6,790	82,087	8.3
	Box van	93,108	7,516	100,624	7.5
	Sedan	815,788	55,994	871,782	6.4

Table 2 Differences in serious-injury risks to cyclists between commercial truck types and sedans

Vehicle travel velocity	Serious-injury risk				p-value
	Sedans (a) (%)	Commercial truck types	(b) (%)	Difference (b)-(a) (%)	
≤30 km/h	5.0	Heavy-duty truck	19.7	14.7	<0.001**
	5.0	Medium-duty truck	9.7	4.7	<0.001**
	5.0	Light-duty truck	6.2	1.2	<0.001**
	5.0	Box van	5.9	0.9	<0.001**
31 km/h–60 km/h	20.1	Heavy-duty truck	35.8	15.7	<0.001**
	20.1	Medium-duty truck	31.3	11.2	<0.001**
	20.1	Light-duty truck	23.3	3.2	<0.001**
	20.1	Box van	21.9	1.8	<0.001**
>60 km/h	39.8	Heavy-duty truck	63.5	23.7	<0.001**
	39.8	Medium-duty truck	55.1	15.3	<0.001**
	39.8	Light-duty truck	39.8	0.0	0.999
	39.8	Box van	34.9	-4.9	0.208

**Significant at the 1% level

Table 3 Cyclist injuries and fatalities, and fatality risks to cyclists at different vehicle travel velocities

Vehicle travel velocity	Vehicle type	Minor injury		Serious injury		Fatality		Total
		(n)	(%)	(n)	(%)	(n)	(%)[1]	(n)
≤30 km/h	Heavy-duty truck	7,252	74.6	1,783	18.3	684	7.0	9,719
	Medium-duty truc	23,522	89.3	2,516	9.6	302	1.1	26,340
	Light-duty truck	68,079	93.4	4,529	6.2	277	0.4	72,885
	Box van	85,598	93.9	5,381	5.9	197	0.2	91,176
	Sedan	751,809	95.0	39,283	5.0	522	0.1	791,614
31 km/h–60 km/h	Heavy-duty truck	1,452	55.9	808	31.1	336	12.9	2,596
	Medium-duty truc	3,219	61.3	1,470	28.0	566	10.8	5,255
	Light-duty truck	7,035	73.1	2,140	22.2	449	4.7	9,624
	Box van	7,400	74.8	2,076	21.0	412	4.2	9,888
	Sedan	62,480	78.0	15,720	19.6	1,884	2.4	80,084
>60 km/h	Heavy-duty truck	84	24.1	146	41.8	119	34.1	349
	Medium-duty truc	84	27.1	103	33.2	123	39.7	310
	Light-duty truck	183	50.1	121	33.2	61	16.7	365
	Box van	110	52.6	59	28.2	40	19.1	209
	Sedan	1,499	48.9	991	32.3	574	18.7	3,064
Total	Heavy-duty truck	8,788	69.4	2,737	21.6	1,139	9.0	12,664
	Medium-duty truc	26,825	84.1	4,089	12.8	991	3.1	31,905
	Light-duty truck	75,297	90.9	6,790	8.2	787	0.9	82,874
	Box van	93,108	91.9	7,516	7.4	649	0.6	101,273
	Sedan	815,788	93.3	55,994	6.4	2,980	0.3	874,762

[1] Fatality risk

Table 4 Differences in fatality risks to cyclists between commercial truck types and sedans

Vehicle travel velocity	Fatality risk				p-value
	Sedans (a) (%)	Commercial truck types	(b) (%)	Difference (b)-(a) (%)	
≤30 km/h	0.1	Heavy-duty truck	7.0	6.9	<0.001**
	0.1	Medium-duty truck	1.1	1.0	<0.001**
	0.1	Light-duty truck	0.4	0.3	<0.001**
	0.1	Box van	0.2	0.1	<0.001**
31 km/h–60 km/h	2.4	Heavy-duty truck	12.9	10.5	<0.001**
	2.4	Medium-duty truck	10.8	8.4	<0.001**
	2.4	Light-duty truck	4.7	2.3	<0.001**
	2.4	Box van	4.2	1.8	<0.001**
>60 km/h	18.7	Heavy-duty truck	34.1	15.4	<0.001**
	18.7	Medium-duty truck	39.7	21.0	<0.001**
	18.7	Light-duty truck	16.7	-2.0	0.347
	18.7	Box van	19.1	0.4	0.885

**Significant at the 1% level

Table 5 Differences in serious-injury risks to cyclists for different vehicle travel velocities

Vehicle type	Serious-injury risk				Serious-injury risk			
	≤30 km/h (a) (%)	31–60 km/h (b) (%)	Difference (b) - (a) (%)	p-value	31–60 km/h (b) (%)	>60 km/h (c) (%)	Difference (c) - (b) (%)	p-value
Heavy-duty truck	19.7	35.8	16.0	<0.001**	35.8	63.5	27.7	<0.001**
Medium-duty truck	9.7	31.3	21.7	<0.001**	31.3	55.1	23.7	<0.001**
Light-duty truck	6.2	23.3	17.1	<0.001**	23.3	39.8	16.5	<0.001**
Box van	5.9	21.9	16.0	<0.001**	21.9	34.9	13.0	<0.001**
Sedan	5.0	20.1	15.1	<0.001**	20.1	39.8	19.7	<0.001**

**Significant at the 1% level

Table 6 Differences in fatality risks to cyclists for different vehicle travel velocities

Vehicle type	Fatality risk				Fatality risk			
	≤30 km/h (a) (%)	31–60 km/h (b) (%)	Difference (b) - (a) (%)	p-value	31–60 km/h (b) (%)	>60 km/h (c) (%)	Difference (c) - (b) (%)	p-value
Heavy-duty truck	7.0	12.9	5.9	<0.001**	12.9	34.1	21.2	<0.001**
Medium-duty truck	1.1	10.8	9.6	<0.001**	10.8	39.7	28.9	<0.001**
Light-duty truck	0.4	4.7	4.3	<0.001**	4.7	16.7	12.0	<0.001**
Box van	0.2	4.2	4.0	<0.001**	4.2	19.1	15.0	<0.001**
Sedan	0.1	2.4	2.3	<0.001**	2.4	18.7	16.4	<0.001**

**Significant at the 1% level

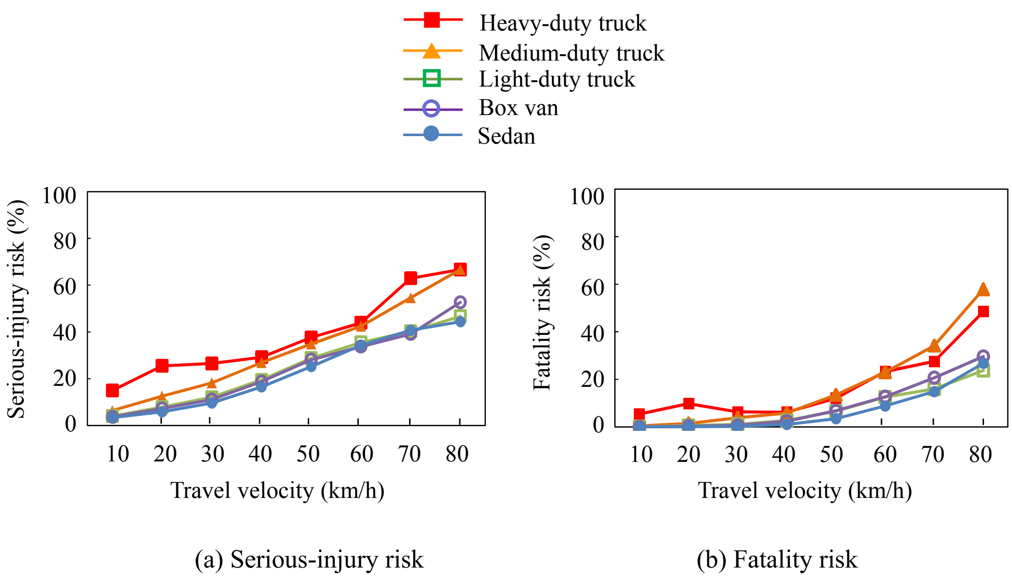


Figure 1 Relationship between serious-injury and fatality risks to cyclists and vehicle travel velocity.

Table 7 Cyclists injuries and fatalities for five vehicle types at different vehicle travel velocities

Vehicle type	Travel velocity (km/h)	Number			
		Minor injury	Serious injury	Fatality	Total
Heavy-duty truck	10	4,282	754	288	5,324
	20	2,288	783	333	3,404
	30	682	246	63	991
	40	643	265	60	968
	50	501	302	110	913
	60	308	241	166	715
	70	70	119	72	261
	80	11	22	31	64
	90	0	2	13	15
	100	1	1	3	5
	over 100	2	2	0	4
	Subtotal	8,788	2,737	1,139	12,664
Medium-duty truck	10	14,115	960	61	15,136
	20	6,792	973	114	7,879
	30	2,615	583	127	3,325
	40	1,919	707	163	2,789
	50	968	518	231	1,717
	60	332	245	172	749
	70	69	83	79	231
	80	8	16	33	57
	90	4	2	8	14
	100	1	1	3	5
	over 100	2	1	0	3
	Subtotal	26,825	4,089	991	31,905
Light-duty truck	10	39,728	1,656	37	41,421
	20	19,496	1,654	127	21,277
	30	8,855	1,219	113	10,187
	40	4,835	1,171	165	6,171
	50	1,668	676	166	2,510
	60	532	293	118	943
	70	132	89	42	263
	80	24	21	14	59
	90	15	7	3	25
	100	2	1	2	5
	over 100	10	3	0	13
	Subtotal	75,297	6,790	787	82,874
Box van	10	47,280	1,811	17	49,108
	20	26,320	2,068	85	28,473
	30	11,998	1,502	95	13,595
	40	5,392	1,245	163	6,800
	50	1,619	633	164	2,416
	60	389	198	85	672
	70	70	45	30	145
	80	9	10	8	27
	90	15	4	1	20
	100	3	0	1	4
	over 100	13	0	0	13
	Subtotal	93,108	7,516	649	101,273
Sedan	10	428,722	15,044	83	443,849
	20	228,378	14,176	184	242,738
	30	94,709	10,063	255	105,027
	40	43,897	8,684	568	53,149
	50	14,346	4,822	695	19,863
	60	4,237	2,214	621	7,072
	70	949	652	279	1,880
	80	286	228	188	702
	90	154	65	44	263
	100	21	31	42	94
	over 100	89	15	21	125
	Subtotal	815,788	55,994	2,980	874,762
Five types of vehicles	Total	1,019,806	77,126	6,546	1,103,478

Analysis 2 (MICRO data)

The MICRO data describe 274 cyclist fatalities resulting from collisions with heavy-duty, medium-duty and light-duty trucks, box vans, or sedans. Of the cyclist fatalities, 0.4% involved heavy-duty trucks, 4.7% involved medium-duty trucks, 2.9% involved light-duty trucks, 2.6% involved box vans, and 89.4% involved sedans. These limited numbers led us to combine heavy-duty, medium-duty and light-duty trucks and box vans into the category of commercial trucks (n=29; 10.6%).

The vehicle travel velocity and impact velocity are compared for commercial trucks and sedans in Figure 2. The figure illustrates the linear regressions ($y = a \times x$) along with the regression coefficients (a). The regression coefficient for commercial trucks was the highest for cyclist fatalities (0.96), followed by serious injuries to cyclists with (0.83) and minor injuries to cyclists (0.51). For sedans, the regression coefficient was the highest for cyclist fatalities (0.92), followed by serious injuries (0.80) and minor injuries (0.74). This implies that as the degree of injury increased, the travel velocity tended to approach the impact velocity. This suggests that the brakes may not have been applied in sufficient time and with appropriate force.

The differences in the linear regression coefficients between minor injuries, serious injuries and fatalities to cyclists are presented in Table 8. For commercial trucks and sedans, there were significant differences in linear regression coefficients between minor and serious injuries ($p < 0.001$) and between serious injuries and fatalities ($p < 0.001$).

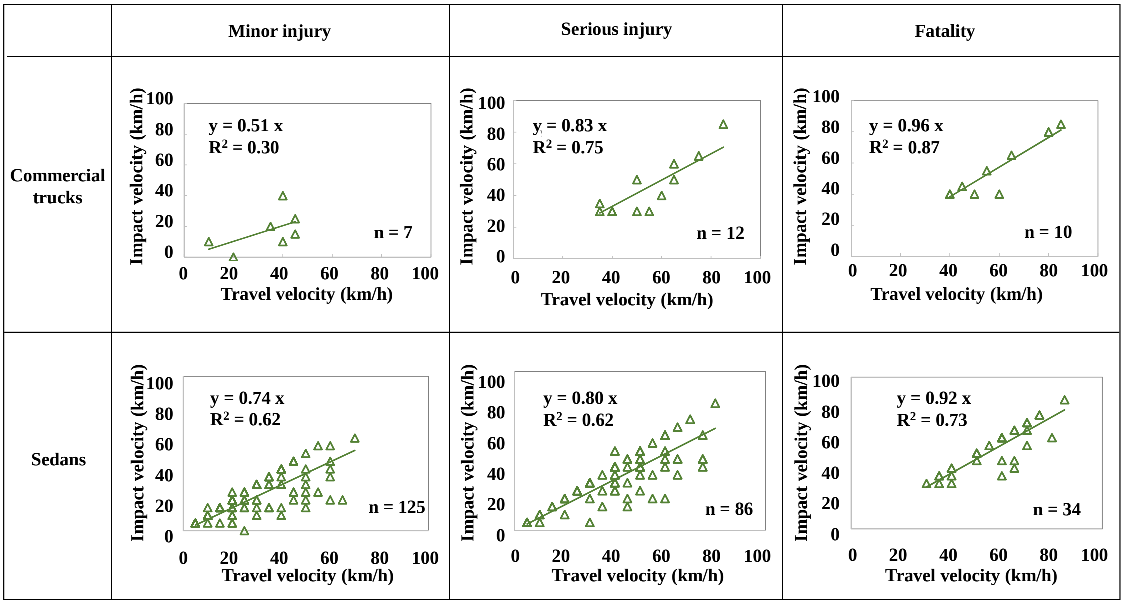
The differences in the linear regression coefficients between commercial trucks and sedans are presented in Table 9. In cases with minor injuries, the linear regression coefficient for commercial trucks was significantly lower than that for sedans ($p < 0.001$). In contrast, in cases with serious injuries, the linear regression coefficient for commercial trucks was higher than that for sedans, but the difference was not significant ($p = 0.072$). In cases with fatalities, the linear regression coefficient in commercial trucks was significantly higher than that for sedans ($p < 0.001$). In the present study, the linear regression coefficients for commercial trucks were used when calculating the serious-injury and fatality risks to cyclists in collisions with heavy-duty trucks, medium-duty trucks, light-duty trucks, and box vans. Similarly, the linear regression coefficients for sedans were used when calculating the serious-injury and fatality risks to cyclists in collisions with sedans.

Analysis 3 (MACRO data)

The serious-injury risks to cyclists in collisions with heavy-duty, medium-duty, and light-duty trucks, box vans, and sedans at 10 km/h increments of vehicle velocity are shown in Figure 3(a) and Table 10. The serious-injury risks to cyclists were ≤20% for light-duty trucks, box vans, and sedans, at impact velocities ≤30 km/h (Table 10). The serious-injury risks to cyclists were ≤20% for medium-duty trucks at impact velocities ≤20 km/h. For heavy-duty trucks, the serious-injury risk was 17% at impact velocities ≤10 km/h. These results indicate that the relationship between serious-injury risk to cyclists and impact velocity depends on vehicle type.

The fatality risks to cyclists in collisions with heavy-duty, medium-duty, and light-duty trucks, box vans, and sedans at 10 km/h increments of vehicle velocity are shown in Figure 3(b) and Table 11. The fatality risk to cyclists was ≤5% for light-duty trucks, box vans, and sedans at impact velocities ≤40 km/h. The fatality risk was ≤5% for medium-duty trucks at impact velocities ≤30 km/h (Table 11). The fatality risk was 6% for heavy-duty trucks at impact velocities ≤10 km/h. Thus, the relationship between fatality risk to cyclists and impact velocity strongly depends on vehicle type.

The fatality risks to cyclists in collisions with heavy-duty trucks were ≤24% at impact velocities ≤60 km/h, ≤15% at ≤50 km/h, and ≤7% at ≤40 km/h. The fatality risks to cyclists in collisions with medium-duty trucks were ≤26% at impact velocities ≤60 km/h, ≤16% at ≤50 km/h, and ≤7% at ≤40 km/h. The fatality risks to cyclists in collisions with light-duty trucks, box vans, and sedans were ≤15% at impact velocities ≤60 km/h, ≤8% at ≤50 km/h, and ≤3% at ≤40 km/h. Thus, the results revealed that a 10 km/h reduction in impact velocity could mitigate fatality risk significantly across the five vehicle types in collisions that occur at >30km/h.



* y = impact velocity, x = travel velocity

Figure 2 Relationship between travel velocity and impact velocity for commercial trucks and sedans.

Table 8 Differences in linear regression coefficients among cyclist injury levels

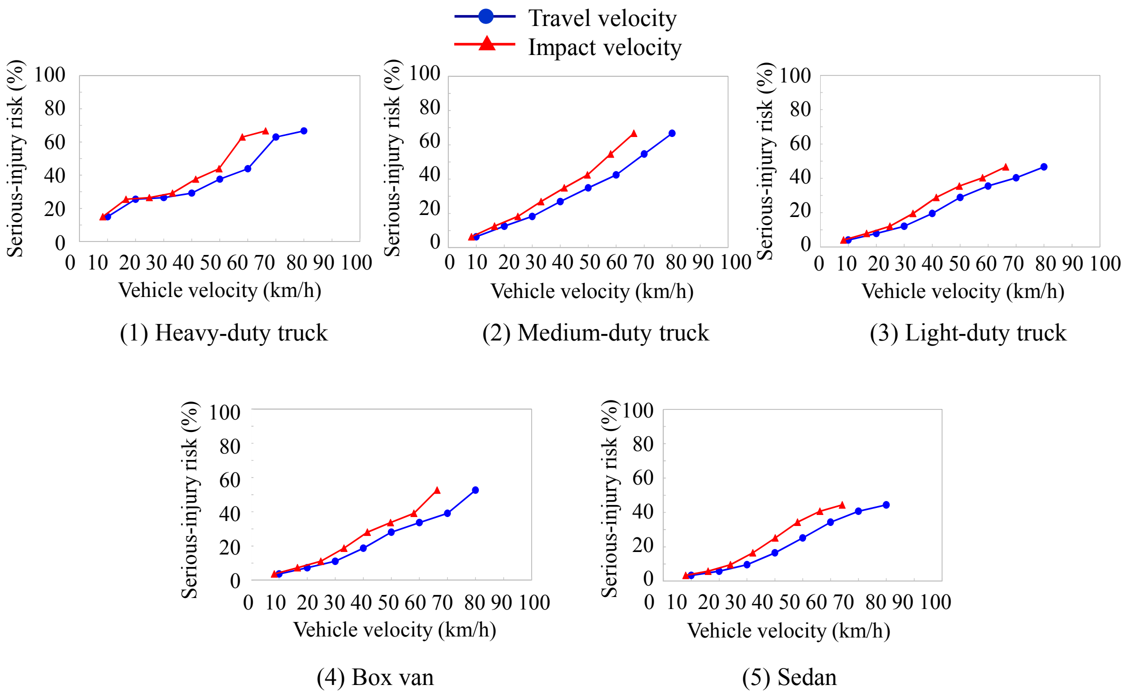
Vehicle categories	Analyses	Minor injury	Serious injury	Serious injury	Fatality
Commercial trucks	Average of linear regression coefficient	0.5125	0.8289	0.8289	0.9560
	Standard deviation of linear regression coefficient	0.1134	0.0453	0.0453	0.0350
	Number	7	12	12	10
	p-value	<0.001**		<0.001**	
Sedans	Average of linear regression coefficient	0.7439	0.8024	0.8024	0.9215
	Standard deviation of linear regression coefficient	0.0234	0.0228	0.0228	0.0224
	Number	125	86	86	34
	p-value	<0.001**		<0.001**	

**Significant at the 1% level

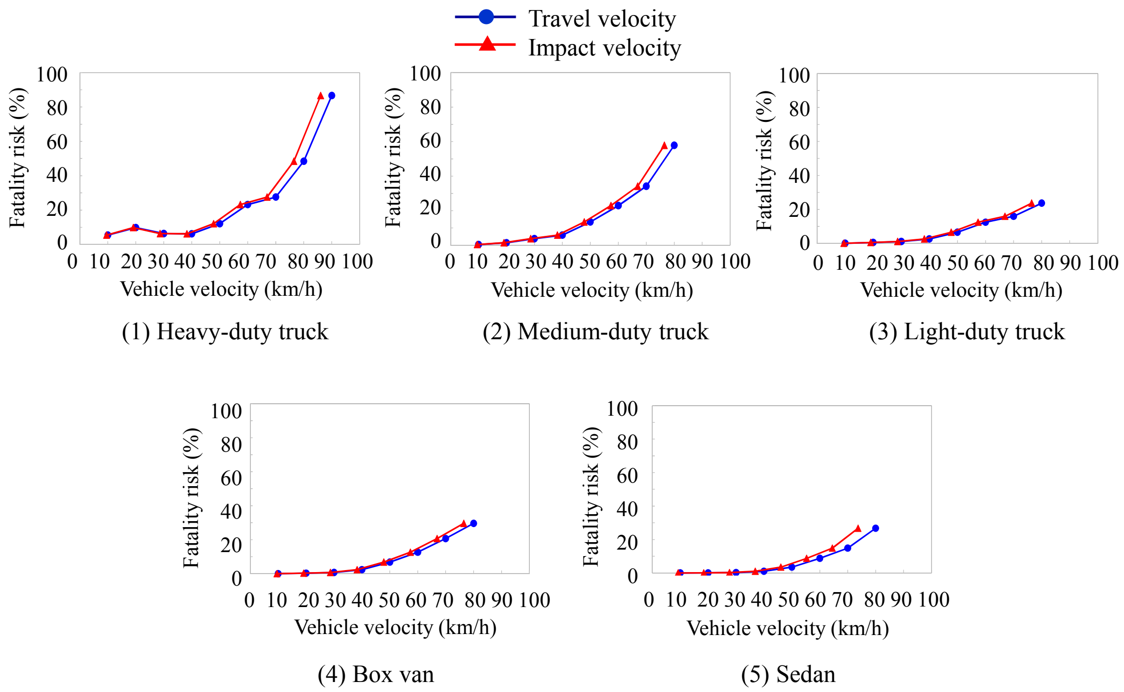
Table 9 Differences in linear regression coefficients between commercial trucks and sedans

Analyses	Minor injury		Serious injury		Fatality	
	Commercial trucks	Sedans	Commercial trucks	Sedans	Commercial trucks	Sedans
Average of linear regression coefficient	0.5125	0.7439	0.8289	0.8024	0.9560	0.9215
Standard deviation of linear regression coefficient	0.1134	0.0234	0.0453	0.0228	0.0350	0.0224
Number	7	125	12	86	10	34
p-value	<0.001**		0.072		<0.001**	

**Significant at the 1% level



(a) Serious-injury risk and impact velocity



(b) Fatality risk and impact velocity

Figure 3 Relationships between serious-injury and fatality risks and vehicle impact velocity.

Table 10 Serious-injury risk to cyclists by impact velocity

Vehicle impact velocity (km/h)	Serious-injury risk (%)				
	Heavy-duty truck	Medium-duty truck	Light-duty truck	Box van	Sedan
10	17	8	5	4	4
20	26	15	10	7	8
30	28	24	17	16	15
40	36	34	27	26	25
50	45	43	36	34	36
60	64	57	42	42	42

Table 11 Fatality risk to cyclists by impact velocity

Vehicle impact velocity (km/h)	Fatality risk (%)				
	Heavy-duty truck	Medium-duty truck	Light-duty truck	Box van	Sedan
10	6	0	0	0	0
20	9	2	1	0	0
30	6	4	1	1	0
40	7	7	3	3	2
50	15	16	8	8	6
60	24	26	13	15	12

Analysis 4 (MACRO data)

Table 12 shows the differences in fatality risk between daytime and nighttime collisions among the five vehicle types. Heavy-duty trucks had the highest fatality risks in daytime (7.8%) and nighttime (13.7%) collisions. Although there were more cyclist fatalities in daytime collisions than in nighttime collisions across all vehicle types, the fatality risk was significantly higher at nighttime than during daytime for all vehicle types.

Table 13 shows the number of cyclist fatalities by road type. At intersections with traffic signals, the number (478) and frequency (59.7%) of cyclist fatalities during daytime was the highest for accidents involving heavy-duty trucks among all types of vehicle (Table 13).

Table 14 shows the frequency of cyclist fatalities at intersections with traffic signals and on straight roads during daytime and at nighttime. The frequency of cyclist fatalities at intersections with traffic signals involving heavy-duty trucks was significantly higher during daytime than that at nighttime. In contrast, the frequency of cyclist fatalities at intersections with traffic signals involving sedans was significantly higher at nighttime than that during daytime. The frequency of cyclist fatalities on straight roads was significantly higher at nighttime than that during daytime for all types of vehicle (Table 14).

Table 15 shows cyclist fatalities by driving scenario in accidents at intersections with traffic signals during daytime and at nighttime among five types of vehicle. Fatalities involving vehicles making a left turn generally increased with vehicle weight. The frequency of cyclist fatalities involving vehicles making a left turn was the largest for heavy-duty trucks both during daytime (67.6%) and at nighttime (52.3%), among all vehicle types. It should be noted that vehicles drive on the left side of the road in Japan.

Table 12 Differences in fatality risk to cyclists between daytime and nighttime

Vehicle type	Daytime					Nighttime					Difference (b) - (a) (%)	p-value
	Minor injury (n)	Serious injury (n)	Fatality (n)	Total (n)	Fatality risk (a) (%)	Minor injury	Serious injury	Fatality	Total	Fatality risk (b) (%)		
Heavy-duty truck	7,364	2,122	801	10,287	7.8	1,524	640	344	2,508	13.7	5.9	<0.001**
Medium-duty truck	23,527	3,248	657	27,432	2.4	3,895	887	334	5,116	6.5	4.1	<0.001**
Light-duty truck	64,085	5,553	565	70,203	0.8	12,104	1,299	222	13,625	1.6	0.8	<0.001**
Box van	77,509	6,105	444	84,058	0.5	16,502	1,451	205	18,158	1.1	0.6	<0.001**
Sedan	624,307	41,570	1,541	667,418	0.2	198,114	14,692	1,440	214,246	0.7	0.4	<0.001**

**Significant at the 1% level

Table 13 Number and frequency of cyclist fatalities in collisions among five vehicle types by road type

Day/night	Vehicle type	Intersection with traffic signals		Intersection without traffic signals		Near intersection		Straight road		Total	
		(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)
Daytime											
	Heavy-duty truck	478	59.7	149	18.6	38	4.7	136	17.0	801	100.0
	Medium-duty truck	221	33.6	237	36.1	63	9.6	136	20.7	657	100.0
	Light-duty truck	132	23.4	305	54.0	29	5.1	99	17.5	565	100.0
	Box van	102	23.0	220	49.5	27	6.1	95	21.4	444	100.0
	Sedan	310	20.1	739	48.0	109	7.1	383	24.9	1,541	100.0
Nighttime											
	Heavy-duty truck	132	38.4	35	10.2	21	6.1	156	45.3	344	100.0
	Medium-duty truck	107	32.0	57	17.1	27	8.1	143	42.8	334	100.0
	Light-duty truck	63	28.4	55	24.8	27	12.2	77	34.7	222	100.0
	Box van	38	18.5	54	26.3	23	11.2	90	43.9	205	100.0
	Sedan	367	25.5	395	27.4	170	11.8	508	35.3	1,440	100.0

Table 14 Frequency of cyclist fatalities in collisions among five vehicle types at intersections with traffic signals and on straight roads during daytime and at nighttime

Vehicle type	Frequency of cyclists' fatalities at intersection with traffic signals				Frequency of cyclists' fatalities on straight road			
	Daytime (a) (%)	Nighttime (b) (%)	Difference (b) - (a) (%)	p-value	Daytime (a) (%)	Nighttime (b) (%)	Difference (b) - (a) (%)	p-value
Heavy-duty truck	59.7	38.4	-21.3	<0.001**	17.0	45.3	28.4	<0.001**
Medium-duty truck	33.6	32.0	-1.6	0.612	20.7	42.8	22.1	<0.001**
Light-duty truck	23.4	28.4	5.0	0.142	17.5	34.7	17.2	<0.001**
Box van	23.0	18.5	-4.4	0.201	21.4	43.9	22.5	<0.001**
Sedan	20.1	25.5	5.4	<0.001**	24.9	35.3	10.4	<0.001**

**Significant at the 1% level

Table 15 Number of cyclist fatalities in collisions among five vehicle types for different driving scenarios at intersections with traffic signals during daytime and at nighttime

	Vehicle type	Start moving		Travel straight ahead		Right turn		Left turn		Others		Total	
		(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)
Daytime													
	Heavy-duty truck	25	5.2	83	17.4	46	9.6	323	67.6	1	0.2	478	100.0
	Medium-duty truck	20	9.0	120	54.3	52	23.5	29	13.1	0	0.0	221	100.0
	Light-duty truck	12	9.1	63	47.7	42	31.8	15	11.4	0	0.0	132	100.0
	Box van	2	2.0	56	54.9	31	30.4	13	12.7	0	0.0	102	100.0
	Sedan	16	5.2	199	64.2	66	21.3	27	8.7	2	0.6	310	100.0
Nighttime													
	Heavy-duty truck	4	3.0	43	32.6	16	12.1	69	52.3	0	0.0	132	100.0
	Medium-duty truck	3	2.8	70	65.4	29	27.1	5	4.7	0	0.0	107	100.0
	Light-duty truck	1	1.6	46	73.0	13	20.6	3	4.8	0	0.0	63	100.0
	Box van	0	0.0	27	71.1	8	21.1	3	7.9	0	0.0	38	100.0
	Sedan	3	0.8	331	90.2	27	7.4	5	1.4	1	0.3	367	100.0

DISCUSSION

This study showed that in cyclist collisions with heavy-duty trucks, the fatality risk at vehicle impact velocity of 20 km/h (9%) was higher than that at 30 km/h (6%) and 10 km/h (6%) (Table 11). This is likely related to the high frequency of cyclist collisions when heavy-duty trucks turned left at intersections with traffic signals (Table 15). In Japan and other countries that drive on the left side of the road, the driver position is on the right side of the vehicle. Heavy-duty truck drivers have a blind spot behind the left side door (Robinson et al. 2016). This increases the risk of accidents between left turning trucks and straight driving cyclists. Driver blind spots change when the vehicle is turning, particularly because the trailer unit always turns along a shorter radius than the cabin unit (ETSC 2015). This results in the driver being unable to see pedestrians and cyclists who are close to the vehicle, particularly when turning. Zeiniger et al. (2015) reported that, in Germany, 90% of all accidents involving commercial trucks occurred at a travelling velocity < 30 km/h, and that vehicles involved in 90 % of cyclist fatalities in blind spot situations were GVW $>7.5 \times 10^3$ kg [7.5 t] trucks. Because the number of the heavy-duty truck-to-cyclist accidents in the MICRO data are so limited (0.4% of 341 cyclist fatalities; n=1), the accident mechanism at low impact velocities must be investigated further in future.

In the present study, it was found that the reduction of impact velocity is a key to reduce serious-injury and fatality risks to cyclists. Matsui et al. investigated the relationship between serious-injury and fatality risks to pedestrians and impact velocity (Matsui et al. 2016a). They showed that the fatality risk to pedestrians of ≤5% was indicated for light-duty trucks, box vans, and sedans at impact velocities ≤30 km/h and for medium-duty trucks at impact velocities ≤20 km/h. The fatality risk to pedestrians was ≤10% for heavy-duty trucks at impact velocities ≤10 km/h. From the results of the present study, the fatality risk to cyclists of ≤5% was indicated for light-duty trucks, box vans, and sedans at impact velocities ≤40 km/h, and for medium-duty trucks at impact velocities ≤30 km/h (Table 11). Thus, at a certain impact velocities, the fatality risk to cyclists is lower than that to pedestrians. There are several potential reasons why the fatality risk to cyclists was different from that to pedestrians: 1) Some cyclists might wear a helmet (Matsui and Oikawa 2015). Several studies have shown that serious-injury and fatality risk is lower for cyclists who wear a helmet (Bambach et al. 2013, Boufous et al., 2012, Matsui and Oikawa 2015). 2) Impact situations between pedestrians and cyclists are be different, for example, pedestrians are impacted by the vehicle directly whereas cyclists are often impacted both directly and indirectly through contact between the vehicle and the bicycle. 3) The travelling velocities of cyclists are likely to be higher than of pedestrians (Oikawa et al. 2016). Further research is necessary to understand the injury mechanism differences between cyclists and pedestrians during impacts by vehicles.

A limitation of the present study is that the data used did not include vehicles that were equipped with CMSs with detection of cyclists ahead of the vehicle, because such data are not yet available. As the number of vehicles with CMSs increase, this study should be repeated using real-world accident data that includes CMSs with cyclist detection to investigate the benefits of such systems on cyclist injury mitigation.

Among the possible collision scenarios, 64% of fatal and 63% of near-miss incidents occurred when cyclists crossed roads in front of passenger cars at intersections (Matsui et al. 2016b). In Japan, cyclist accidents occur most frequently in Tokyo (ITARDA 2014). Oikawa et al. investigated cyclist behavior at an intersection in Tokyo, where traffic accidents are frequent (Oikawa et al. 2016). They showed that these accidents occurred because of a combination of factors including bicycle velocity of operation, lack of cyclist's confirmation of safety, and poor cyclist's visibility due to obstacles at corners of intersections. In near-miss incidents in which cyclists moved in front of passenger cars, the average time to collision where the driver's view was obstructed (1.95 s) was significantly shorter than those where the driver's view was unobstructed (3.26 s) (Matsui et al. 2016b). Current CMSs may not be able to detect cyclists in such cases where time to collision is very short. Serious injuries and fatalities in cyclists could be decreased by the development and deployment of CMSs in all vehicles, including commercial trucks. CMSs can detect cyclists even in an obstruction like a building or other vehicle which is resulted in poor visibility situations, and can react more quickly than human drivers can, thus reducing the impact velocity even when the driver's view is obstructed.

From these results, it is clear that CMSs that can detect cyclists are extremely important for cyclist safety. They are important not only for sedans but also for commercial trucks, considering the high fatality risk to cyclists of commercial trucks even at low impact velocities. From 2018, the European New Car Assessment Program (Euro-NCAP) will begin using a safety assessment test for new passenger cars with CMSs with cyclist detection (Camp et al. 2016). This test will include three scenarios: a cyclist moving in front of the test car from an unobstructed view (lateral impact scenario); a cyclist moving in front of the test car using the same lateral impact scenario with a shorter time to collision; and the test car following a forward moving cyclist. The introduction of this assessment method reflects the growing popularity of passenger cars with CMSs in the European car market. Though the number of passenger cars sold equipped with CMSs is likely to grow, few commercial trucks equipped with such systems are likely to be introduced in the near-term. The findings from the present study suggest that for CMSs that can detect cyclists effectively, there are potential benefits to the introduction of such CMSs on cyclist injury mitigation.

Recently, the European Commission (EC) added CMSs with cyclist detection into their general safety policy that will be used in future type approval regulations in Europe (EC 2017). New passenger cars will be required to install such CMSs from 2026. Furthermore, new vehicles with GVW $\geq 3.5 \times 10^3$ kg [3.5 t] will be required to have cyclist detection from 2028. The relationships between commercial truck–cyclist impact velocity and the serious-injury and fatality risks to cyclists described in the present study may be useful for European regulations when they consider acceptable reference values for impact velocity.

One of the limitations of this study is the lack of information regarding bicycle velocity, traveling direction relative to vehicle movement, and the position of cyclists relative to the vehicle when collisions occurred. Generally, velocity vectors affect the impact location and velocity of the cyclist on impact with the vehicle. Thus, the velocity vectors affect the fatality and serious-injury risks to cyclists. For example, if a cyclist is traveling at the left side of a truck making a left turn, the velocity component hitting the cyclist would be quite different from the travel velocity of the truck. Similarly, a cyclist traveling in the same direction as its collision partner would result in a different impact velocity from one travelling in the opposite direction to its collision partner. These scenarios were not taken into consideration in the current study. In future, the fatality and serious-injury risks to cyclists should be clarified in more detail under different conditions in which cyclists were involved in frontal, rear-end, or lateral collisions with vehicles.

The fatality frequencies were significantly higher at nighttime than during daytime (Table 12). The frequency of cyclist fatalities on straight roads was significantly higher at nighttime than during daytime (Table 14). These results support the report from ITARDA (2011). ITARDA reported that vehicle-to-rear-end-of-bicycle impacts accounted for 72% at nighttime, while they accounted for 28% during daytime. In vehicle-to-rear-end-of-bicycle impacts, 78% of the corresponding accident cases occurred on straight road and the vehicle travel velocities were high compared with other approach patterns. The reason for more frequent cyclist fatalities on straight roads at nighttime was considered the combined effect of vehicle-to-cyclist approach pattern such as vehicle-to-rear-end-of-bicycle impact and higher vehicle travel velocity. A system that can be linked to CMSs is an intelligent night-vision system which detects critical objects such as pedestrians or cyclists at night, in low-light or low-visibility conditions (ETSC 2015). Such systems either display collected data to the driver, for them to decide what action to take, or intelligently analyze collected data and warn the driver of a potential collision. If an intelligent night-vision system is linked to a CMS with cyclist detection, it can be expected to reduce the number of accidents involving cyclist fatalities.

CONCLUSION

In the present study, we investigated the relationship between impact velocity and the serious-injury and fatality risks to cyclists in collisions with heavy-duty, medium-duty, and light-duty trucks; box vans; and sedans. The fatality risk was ≤5% for light-duty trucks, box vans, and sedans at impact velocities ≤ 40 km/h and for medium-duty trucks at impact velocities ≤30 km/h. The fatality risk was 6% for heavy-duty trucks at impact velocities ≤10 km/h. The results also revealed that a 10 km/h reduction in impact velocities could mitigate the severity of cyclist injuries at impact velocities ≥30 km/h for all five analyzed vehicle types.

We also investigated the effects of road type and driving scenario on the frequency of cyclist fatalities due to collisions with the five vehicle types. The frequency of cyclist fatalities at intersections with traffic signals involving heavy-duty trucks was significantly higher during daytime than that at nighttime. Fatalities involving vehicles making a left turn generally increased with vehicle weight. The frequency of cyclist fatalities involving vehicles making a left turn was the largest for heavy-duty trucks both during daytime (67.6%) and at nighttime (52.3%).

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