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Whiplash Injury Conditions of Rear-End Collisions at Low-Speed

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요 약

국내에서 발생하는 교통사고에 의한 인적피해의 정도는 꾸준히 감소하고 있으나 경상자와 부상신고자수는 증가하는 추세이다. 그러나 도덕적 해이로 인한 허위・과다 치료와 입원으로 발생하는 사회적 비용은 전 세계적으로 사회, 경제적 문제로 대두되는 실정이다. 경미한 교통사고의 유형 중, 추돌사고의 경우 피해차량 즉, 피추돌차량 탑승자가 주로 호소하는 질병은 해부학적, 방사선학적 근거가 없는 임상적 추정에 의한 목 상해(경추염좌)이다. 그러나 국제적인 상해 분류기준인 AIS(Abbreviated Injury Scale)와 경추염좌를 비교했을 때 임상적 추정에 의한 목 상해는 상해라 보기 어렵다. 따라서 본 연구에서는 추돌사고에 연루된 추돌차량과 피추돌차량의 중량과 충돌속도가 탑승자의 목 상해에 어떤 영향을 미치는지 알아보기 위해, MADYMO를 활용하여 중량과 충돌속도를 다양하게 반영한 총 100가지 시나리오의 추돌사고를 재현하였다. 그리고 결과 값인 피추돌차량의 속도변화량과 충격가속도 값을 상해역치와 비교하였다. 그 결과 동일한 중량 간의 추돌사고에서 충돌속도 15km/h 이상일 때 상해가 발생할 가능성이 큰 것으로 나타났으며, 중량을 고려하지 않을 경우 충돌속도 15km/h 일 때 36%, 20km/h이상일 때 약 84%의 상해 발생 가능성이 나타났다.

핵심어 : 목상해, 추돌 교통사고, 저속, 마디모, 시뮬레이션, 임계치

ABSTRACT

As the number of reported injuries has tended to increase over time, large hospitalization expenditure from excessive medical treatments and hospitalization, and insurance frauds associated with moral hazard in minor collisions have caused a global societal problem. Many occupants of rear-ended vehicles involved in rear-end collisions complain of whiplash injury, which is also known as neck injury, without any anatomical and radiological evidence. With only clinical symptoms, stating that a whiplash injury is a type of injury defined by the Abbreviated Injury Scale would be difficult. Therefore, this study focuses on minor rear-end collisions, where the rear-ender vehicle collides with the rear-ended vehicle at rest. The mathematics dynamic model is employed to simulate a total of 100 rear-end collision scenarios based on various weights and collision speeds and identify how the weights and speeds of both vehicles influence the risk of whiplash injury in occupants involved in minor rear-end collisions. The possibility of an injury is very high when the same-weight vehicles are involved in accidents at collision speeds of 15 km/h or higher. The possibilities are 36% and 84% with collision speeds of 15 km/h and 20 km/h, respectively, if weights are disregarded.

Key words : Whiplash injury, Rear-end collisions, Low-speed, MADYMO, Simulation, Threshold

Ⅰ. Introduction

1. Background and Purpose

The number of reported injuries has increased by approximately 2,000 people per year even though the number of serious injuries has been continuously decreasing (Korea Road Traffic Authority, 2014). A rear-end collision is one of the various traffic crash types, where the front part of a vehicle hits the rear side of the vehicle in front of it (Schroeder et al., 2010). In Korea, the driver of the rear-ender vehicle, which is also known as the following vehicle, in a rear-end collision is generally considered to be at fault because of not leaving enough stopping distance or lack of attention. Consequently, the driver of this vehicle almost always compensates for all the loss resulting from the collision. The damage on the rear-ended and rear-ender vehicles is generally not severe when the vehicles involved travel at low speed (Mishimura et al., 2015). Therefore, the majority of rear impacts result in no injury or in temporary symptoms (Krafft et al., 2005). Therefore, insurance claims may not accept it even if an occupant (or occupants) in the rear-ended vehicle claims to have sustained a bodily injury. The country's hospitalization rate for whiplash injury arising from auto insurance plans amounts to 79.2% (Kim, 2015). As a result, societal costs from abnormal insurance claims, including frauds, excessive medical treatments, and hospitalization because of minor collisions, have emerged as a societal problem (Santolino et al., 2012; Mishimura et al., 2015). In addition, moral hazard is considered as a huge reason for the high hospitalization rate and costs. This study is conducted to identify the possibility of a whiplash injury in low-speed rear-end collisions using the mathematics dynamic model (MADYMO). MADYMO has been employed to simulate a total of 100 rear-end collision scenarios based on various weights and impact speeds. The simulation aims to identify how the weights and speeds of both vehicles influence the severity of an occupant's whiplash injury in minor rear-end collisions.

2. Research Scope and Method

This research focuses on minor rear-end collisions, where the rear-ender vehicle collides with the rear-ended vehicle at rest. Only compact and medium-sized vehicles, sports utility vehicles (SUVs), minivans, and small trucks are considered in the simulation due to their high market penetration rates. The vehicle weights and speeds in rear-end collisions are classified to simulate a total of 100 scenarios. MADYMO is employed to examine how the speeds of the rear-ender vehicles and the weight difference between the two vehicles affect speed change (i.e., delta-V) and impact acceleration of the rear-ended vehicle under these simulation scenarios. The simulated speed change and impact accelerations from vehicle weights and collision speeds are compared with the injury threshold.

Ⅱ. Literature Review

1. Whiplash Injury

A whiplash injury is the most frequent injury obtained from rear-end collisions. However, a reported whiplash injury may be hardly accepted as an actual injury if it only includes whiplash symptoms, which do not require medical treatment. The injury is legally specified as a physiological function disorder. The Abbreviated Injury Scale (AIS), which is internationally known as an injury categorization code, classifies the severity of injuries as follows: minor (AIS 1), moderate (AIS 2), serious (AIS 3), severe (AIS 4), critical (AIS 5), and maximum (AIS 6). AIS 1 (i.e., minor) includes slight injuries and those that do not require special medical treatments. AIS 2 (i.e., moderate) includes injuries that are not life-threatening, but involve some treatments (Cho et al., 1989). Cho et al.(1998) classified a whiplash injury into AIS 2 (moderate) if the pain could only be addressed based on anatomical and radiological evidence. Studies on injury severity and duration caused by rear-end collisions have been conducted since the mid-1990s (Yasmin et al., 2014). Investigations on the injury threshold have been followed to identify conditions that cause whiplash injury (Tumbas and Smith, 1988; Cheng and Guenther, 1989; Robinette et al., 1994; Kornhauser, 1996; Hoyes and Henderson, 2013). The injury threshold is defined as a minimum value to cause an injury. Speed change (delta-V in km/h) and collision acceleration (i.e., impact acceleration in g) are considered as the measures of effectiveness for the injury threshold in rear-end collision cases. Delta-V is defined as the speed change from an initial speed at collision to a common speed, where two engaged vehicles reach the same speed after collision. Impact acceleration is defined as the speed variation per unit of time. The impact acceleration value increases when the collision time is short, and the speed variation is large. The following section presents the injury threshold and the simulation tool, MADYMO.

2. Prior Studies on Thresholds for Whiplash Injury

Wolley et al.(1991) found that whiplash injuries based on magnetic resonance imaging observations did not occur under the condition of delta-V being approximately 8 km/h and the peak collision acceleration being 5 – 6g. In their test, only four out of five injured people had temporary headaches, which disappeared right away. Only one woman had minimal neck strain, and no symptom has been reported within one year. Szabo et al.(1994) showed that whiplash injuries did not occur under the condition of delta-V being 10 km/h. Healthy occupants who also maintained proper vehicle positions were not injured in a rear-end collision with a delta-V of up to 8 km/h. McConnell et al.(1995) found that the symptoms of whiplash and permanent muscle injuries did not appear in occupants of a rear-ended vehicle with a delta-V of up to 8 km/h. In their experiment, neck and shoulder strain injuries and compressibility inflammation in a neck’s back muscle increased at delta-V of 8 km/h or higher. Consequently, they claimed that the injury threshold could be 8 km/h. Hell et al.(1999) presented a result showing that the symptoms of a whiplash injury continued in almost every occupant in a rear-end collision with delta-V of 10 – 15 km/h. This result was similar to those of Ono and Kaneoka(1997) and Siegmund(1997) based on volunteer experiments. Braun et al.(2001) showed that adults, who were aided with proper head restraints, in the normal position at a rear-ended vehicle could endure less than 7.2 km/h in terms of delta-V. Based on the result, they claimed that 8 km/h delta-V may be the injury threshold for rear-end collisions. Krafft et al.(2002) and Kullgren et al.(2003) concluded that the symptoms that continued for more than one month occurred in rear-end collisions with an average acceleration of 4.5 g or higher and delta-V of 10 km/h or higher. Krafft et al.(2005) also collected a set of crash information from the vehicle black boxes of about 60,000 cars since 1995 at Folksam, Sweden. From 150 rear-end collisions, only 207 occupants in the front seats who did not have a neck injury were analyzed. Accordingly, 20% of whiplash injury remained for more than one month. The collisions associated with the whiplash injuries occurred with a speed variation of more than 8 km/h and an average acceleration of more than 5 g. Lim et al.(2014) conducted a total of 13 vehicle collision tests using MADYMO and the BioRID II dummy with different vehicle sizes (i.e., compact, medium, and large) at different collision speeds (i.e., 8 km/h, 12 km/h, and 16 km/h) with 40% offset. The risk of a whiplash injury was less than 10% based on the experimental results. Most of the damages are bumper-oriented, including a bumper beam when the speed change was 10 km/h or less and the average collision acceleration was 2 g or less. Damage on the rear-ended vehicles and the severity of a whiplash injury also appeared to increase when the weights and speeds of the rear-ender vehicles increased. <Table 1> shows a summary of the injury thresholds presented in prior studies.

<Table 1> Summary of whiplash injury thresholds

Prior studies	Suggested whiplash injury thresholds
Wolley et al. (1991), Szabo et al. (1994)	Delta-V: 8 – 10 km/h Max. collision acceleration: 5 – 6 g
McConnell et al. (1995)	Delta-V: 8 km/h
Ono and Kaneoka (1997), Siegmund et al. (1997)	Max. delta-V: 10.9 km/h
Hell et al. (1998)	Delta-V: less than 10 km/h
Braun et al. (2001)	Delta-V: 8 km/h
Krafft et al. (2002), Kullgren et al. (2003)	Delta-V: 10 km/h Ave. collision acceleration: 4.5 g
Krafft et al. (2005)	Delta-V: 8 km/h Ave. collision acceleration: 5 g
Lim et al. (2014)	Delta-V: less than 10 km/h Ave. collision acceleration: 2 g

3. MADYMO

A simulation is broadly used to analyse vehicle safety and car accidents because of the limitations in using real people and vehicles. A simulation tool can save time and cost. The process also promises accuracy. Take for example the PC-Crash. This tool is a crash-test simulation tool widely employed to study a vehicle trajectory right after crash for vehicle-to-vehicle and vehicle-to-objects. Accordingly, MADYMO is a program used to examine and evaluate the damage inside and outside of vehicles, safety of pedestrians and occupants in these vehicles, and performance of safety devices in vehicles. MADYMO is a software package developed by TNO Automotive (Netherlands) to study the dynamics of vehicle and occupant movements. The software provides a human body dummy model and a 3D dynamical vehicle analysis. The dummy models can be used to ensure the safety of vehicle occupants and pedestrians. The whiplash injury is considered as the most frequent injury in vehicle occupants. Accordingly, diverse studies have been performed to reduce the whiplash injury severity using the dummy models in MADYMO. Several dummy models have also been provided in MADYMO to reflect different types of accidents, such as head-on, side, and rear-end collisions. MADYMO emulates vehicles and occupants by operating the multi-body (MB) system capable of interconnecting the parts of a human body using kinematic joints.

The software can be used to simulate safety equipment, including seat belts and airbags, because it is able to design deformable components and reflect the characteristics of each element through finite element analysis. The computational fluid dynamics module can also perform a simulation to study the degree of impacts and predict the contact area between an airbag and an occupant when the airbag deploys. MADYMO can operate with MATLAB, LS-DYNA, and PAM-CRASH, among others.

4. Prior Studies Using MADYMO

The National Highway Traffic Safety Administration (NHTSA) hosts the International Technical Conference on the Enhanced Safety of Vehicles (ESV) every two years. It has been known through the conference that many studies have been actively conducted on various safety items to improve a vehicle occupant's safety through simulation and dummy models available in the MADYMO. The whiplash injury, which usually results from rear-end collisions, is affected by seats and head restraints. Kleinberger et al.(1999) used MADYMO to illustrate the settings of seats and head restraints for head constraint conditions that reduce whiplash injuries. Choi(2000) employed the MADYMO to study the impact of seats and active headrest designs on neck injuries during rear-end collisions. Lee et al.(2000) found that seat characteristics, especially seat backrest angles, which influence the whiplash injury severity level, are factors to reduce the occupant's whiplash injuries during rear-end collisions. McCray(2001) used the MADYMO to emulate the head-on collision of heavy school buses under different seat belt and seat conditions. He addressed the need to study the conditions of safety seats for occupants and safety restraint devices by estimating the impact acceleration and head injury criteria for 2- and 3-point belt and belt size. Baek et al.(2012) used the BioRID III dummy provided by the MADYMO in developing optimized seats to reduce whiplash injury in rear-end collisions. The whiplash injury was affected by seat safety based on various head restraints with different materials and shapes; physical and material property on seats, angles, and interior spring; and body seating position, among others. Acar et al.(2013) also conducted a MADYMO simulation to study the effects of seat belt and airbag deployment on fetuses.

5. Suggestions on Literature Review

After examining the previous studies, we found that a whiplash injury did not appear or got better within a short duration under the following circumstances: the rear-ender vehicle's delta-V of 8 km/h or less; an average collision acceleration of 3 g; and a maximum collision acceleration of 5 g or less. The collision speeds and weights of the rear-ended vehicles can affect the severity of vehicular damage and occupant injuries during rear-end collisions. Furthermore, the weights and speeds of the rear-ended vehicles right before colliding affect vehicle occupants. However, most studies have shown the relationship between an injury and delta-V as well as the collision acceleration suffered by the rear-ended vehicle. Complicated procedures also need to be accomplished to simulate or test using a real vehicle and evaluate the possibility of injury in occupants of rear-ended vehicles. This study aims to simulate the effects of vehicle weights and collision speed of the rear-ender vehicle on the collision acceleration and delta-V of the rear-ended vehicle using the MADYMO. The results are then compared with the selected injury threshold.

Ⅲ. Analysis Of Rear-end Collisions

1. Severity Rate by/of Violation Types

In Korea, 29.3% of traffic collisions are rear-end collisions. This study compares the types of regulation violations associated with rear-end collisions in terms of the severity rate. The severity rates are calculated by dividing the number of deaths with the number of collisions. Accordingly, speeding shows the highest severity rate as shown in <Table 2>.

<Table 2> Severity rate by/of violation types in rear-end collisions

Types	Year 2011	Year 2012	Year 2013
Speeding	15.79	11.76	29.49
Crossing a center line	1.83	1.58	2.18
Traffic signal violation	1.64	0.66	1.25
Reckless driving	1.38	1.52	1.44
Lane violation	0.85	0.62	1.81
Blocking right-turn and through movement	0.53	0.46	0.44
Illegal U-turn	0.41	1.05	0.62
Lack of sufficient stopping distance	0.30	0.34	0.32
Moving violation in intersection	0.26	0.42	0.62

The result shows that the collision speed is a critical factor that influences the collision severity. Therefore, this study attempts to evaluate the relations between speed change and whiplash injury severity.

2. Whiplash Injury in Rear-end Collisions

In a rear-end collision, the rear-ended vehicle is thrown forward right. The posture of the occupants in the rear-ended vehicle changes by the inertia to maintain the condition right before colliding. The main body attached to the seat moves forward at the same speed with the vehicle (or seat). However, the head and neck move forward a little bit later than the body. This different motion at that time between the body and the head/neck causes strain (back and forth or left and right) on the muscles, ligaments, and joints in the neck. A whiplash injury can occur when the twists are beyond physiological limits. The whiplash injury from a minor collision is a cervical spine sprain that needs medical treatment for about two weeks. Clinical evaluation for the cervical spine sprain is provided to a patient who suffers from neck pain although it is difficult to examine through pathological anatomy. Therefore, many occupants of rear-ended vehicles involved in rear-end collisions claim to suffer from cervical spine sprain. These occupants then request excessive medical treatments and hospitalization even though they do not have serious symptoms.

3. International Activities to Prevent Insurance Fraud

Even abroad, a whiplash injury causes a social problem because of its difficulty of diagnosis (Santolino et al., 2012). For prevention, Thatcham in England and DSD in Austria have developed the Whiplash Injury Tool Kit (WITkit) to identify the risk of a whiplash injury in rear-end collisions. This kit has been established based on the difference of the kinetic energy among vehicles, data regarding structural features, and evaluation criteria for the whiplash injury. The degree of vehicle damage, occupants' physical conditions, and risk of injuries can be estimated if vehicle information, accident types and locations, and traffic conditions are entered. Insurance companies in England perform detailed investigations on claims, where the risk of a whiplash injury estimated by the WITkit program is 50% or less. Moreover, a whiplash injury is not accepted in Germany when the speed change of the rear-ended vehicle is 11 km/h or less (Kim, 2015).

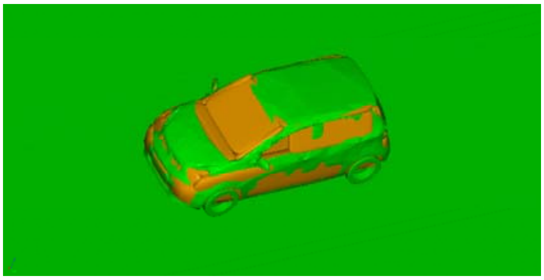
Ⅳ. Simulation Using Madymo

1. Selection of Vehicle Types and Collision Speeds

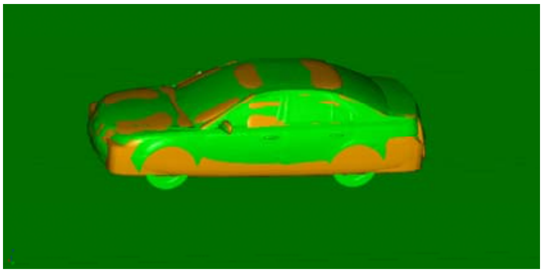
This research emulates collisions using the MADYMO to imitate real collisions and examine the possibility of a whiplash injury in occupants under the following conditions: development in estimating delta-V and collision acceleration of the rear-ended vehicle at different weight combinations of the rear-ended and rear-ender vehicles and different collision speeds of the rear-ender vehicle. The proportion of medium-sized vehicles involved in rear-end collisions is significantly high. Various vehicle types are used in the simulation because fraud/excess hospitalization caused by moral hazard in minor rear-end collisions occur even in situations, where a light vehicle collides with a heavy vehicle. Heavy buses and trucks, which are significantly heavier than medium-sized vehicles, are not included in the simulation. This study considers compact and medium-sized vehicles, SUVs, minivans, and small trucks in the simulation because of their various weights. The following vehicles are selected after considering their popularity in Korea:

- "Morning" (940 kg): manufactured by Kia Motors as the compact vehicle
- "Sonata" (1460 kg): manufactured by Hyundai as the medium-sized vehicle
- "Sorento" (1840 kg): manufactured by Kia Motors as the SUV
- "Starex" (2440 kg): manufactured by Hyundai for the minivan
- "Porter" (1900 kg): manufactured by Kia as the small truck

The occupant's weights and vehicle loads should be considered well. Therefore, the simulation simply uses the total weights of 1,000, 1,500, 2,000, 2,500, and 3,000 kg for compact and medium-sized vehicles, SUV, minivan, and small truck, respectively, as the MB model for the shape of each vehicle (Figs. 1 – 5). There exists a point, where two vehicles reach the common speed, despite the collisions between two vehicles being completed through mutual momentum exchange. The delta-V is the difference between the speeds before colliding to the common speed. This speed change is an important indicator in determining the possibility of a neck injury in occupants of the leading vehicle during rear-end collisions (Krafft et al., 2005; Hoyes and Henderson, 2013). A collision speed of less than 25 km/h, which causes low damage on passengers and vehicles, has been selected to evaluate the possibility of whiplash injury in vehicle occupants during minor rear-end collisions. The law of momentum conservation states that if the plastic deformation involved in real collisions is not considered, the speed change becomes 5 km/h when the rear-ender vehicle at a 10 km/h speed collides with the rear-ended vehicle at rest having the same weight. Therefore, it is calculated close to the threshold when a vehicle's collision speed should be 20 km/h to achieve a speed variation of 10 km/h and realize the whiplash injury threshold. Accordingly, collision speeds are set to 10, 15, 20, and 25 km/h.

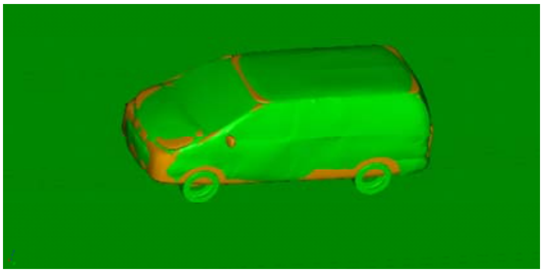


<Fig. 1> Compact vehicle model (i.e., Morning)



<Fig. 2> Medium-sized vehicle model (i.e., Sonata)

<Fig. 3> SUV model (i.e., Sorrento)



<Fig. 4> Minivan vehicle model (i.e., Starex)

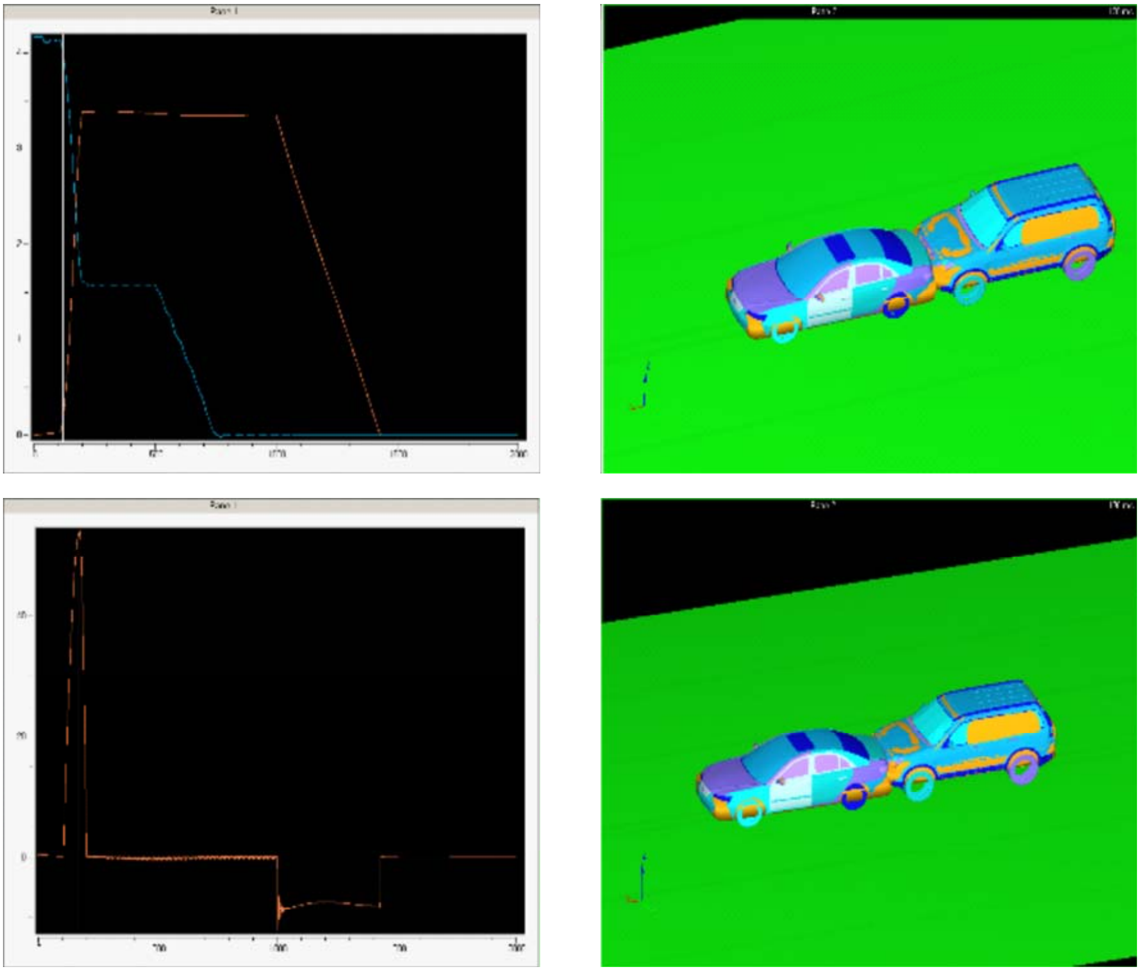
<Fig. 5> Small truck model (e.g., Porter)

2. Simulation Settings

The results presented in this paper are simulation results. Therefore, it is noted that the values of parameters used in MADYMO directly affect the simulation results. For the simulation, the following three parameters were predetermined based on the manual and other researches. The simulation time is set to 2 s to consider the duration for a movement and complete stop after colliding. The rear-ended vehicle speed is set to 0 km/h. The initial gap time between both vehicles is adjusted to guarantee about 0.5 s between the collision of the two vehicles and starting the simulation. The scenarios to be simulated comprise 100 cases, including five types of rear-ended vehicles, five types of rear-ender vehicles, and four speed levels.

3. Simulation Results

The threshold is compared with a set of information comprising vehicle speeds and acceleration estimated from the MADYMO simulation. Speed and acceleration graphs and a 3D animation are used to verify the results of each scenario. The injury threshold is set to 8 km/h (delta-V) and 5g (collision acceleration) based on the results of the prior studies.



(a) Speed and acceleration time history (b) MADYMO animation screen

<Fig. 6> SUV model (i.e., Sorrento)

4. Simulation Results of the Compact Vehicle used as the Rear-ended Vehicle

The simulation results of 20 scenarios using the compact vehicle as the rear-ended vehicle are presented in <Table 3>. The higher delta-V and collision accelerations are estimated according to the general physical laws as the rear-ender vehicle weights and speeds increase. The simulated delta-V of the compact vehicle during a compact vehicle collision is likely to be higher than 8 km/h when the rear-ender vehicle speed is higher than 20 km/h. However, the simulated collision acceleration is higher than 5g when the collision speed is higher than 15 km/h. The estimated delta-V and collision acceleration values are very close to the injury thresholds at 10 km/h of the collision speed of the SUV, minivan, and small truck, which weigh heavier than the double weight of the compact vehicle.

<Table 3> Simulation results of the compact vehicle

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
Compact vehicle	Compact vehicle	10	4.91	4.24
		15	7.39	6.19
		20	9.86	8.42
		25	12.33	10.41
	Medium-sized vehicle	10	5.84	4.50
		15	8.78	6.83
		20	11.73	9.41
		25	14.67	11.67
	SUV	10	6.49	4.93
		15	9.76	7.34
		20	13.07	9.70
		25	16.20	11.89
	Minivan	10	6.49	4.81
		15	9.73	7.19
		20	12.96	9.63
		25	16.18	11.99
	Small truck	10	7.03	4.99
		15	10.55	7.44
		20	14.03	9.94
		25	16.85	12.04

Note: The shaded cells show higher values than the injury threshold.

5. Simulation Results of the Medium-sized Vehicle used as the Rear-ended Vehicle

<Table 4> summarizes the simulation results. Both delta-V and acceleration are likely higher than the injury threshold when the speed of the compact vehicle used as the rear-ender vehicle is higher than 20 km/h. Both parameters are higher than the injury threshold when heavier vehicles with speeds higher than 15 km/h collide with

rear-ender vehicles (i.e., medium-sized vehicles). It is likely that the injury threshold is met when the collision speed is higher than 20 km/h during the collision between same-sized vehicles.

<Table 4> Simulation results of the medium-sized vehicle

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
Medium-sized vehicle	Compact vehicle	10	4.07	3.02
		15	6.07	4.53
		20	8.07	6.07
		25	10.05	7.95
	Medium-sized vehicle	10	4.98	3.41
		15	7.46	5.13
		20	9.93	6.83
		25	12.39	8.54
	SUV	10	5.66	3.66
		15	8.47	5.53
		20	11.27	7.33
		25	14.06	9.14
	Minivan	10	5.66	3.83
		15	8.43	5.57
		20	11.21	7.39
		25	13.98	9.26
	Small truck	10	6.20	4.66
		15	9.28	6.38
		20	12.35	7.73
		25	15.39	9.76

Note: The shaded cells show higher values than the injury threshold.

6. Simulation Results of the SUV used as the Rear-ended Vehicle

The delta-V and collision acceleration are likely higher than the injury threshold when the compact vehicle collides with the SUV at a speed of 25 km/h or less. The possibility of injury to the occupants is also high when the medium-sized vehicle hits the SUV at a speed of 20 km/h or higher. Meanwhile, the delta-V is higher than the injury threshold when the SUV, minivan, and small truck collide at a speed of 15 km/h as shown in <Table 5>.

7. Simulation Results of the Minivan used as the Rear-ended Vehicle

The possibility of injury for the minivan occupants is high when the compact vehicle collides at a speed higher than 25 km/h or equal (<Table 6>). On the other hand, the occupants are less likely to sustain a whiplash injury when the medium-sized vehicle, SUV, and minivan hit the minivan at a speed of 15 km/h or less. The injury is also likely to occur when the small truck collides at a speed of 15 km/h or higher.

<Table 5> Simulation results of the SUV

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
SUV	Compact vehicle	10	3.34	2.36
		15	5.07	3.76
		20	6.75	4.96
		25	8.43	6.03
	Medium-sized vehicle	10	4.23	2.90
		15	6.40	4.11
		20	8.53	5.49
		25	10.68	6.83
	SUV	10	4.89	3.19
		15	7.43	4.51
		20	9.90	5.98
		25	12.37	7.01
	Minivan	10	4.97	3.04
		15	7.43	4.54
		20	9.89	6.12
		25	12.39	7.42
	Small truck	10	5.46	3.15
		15	8.22	4.62
		20	10.98	6.24
		25	13.69	7.17

Note: The shaded cells show higher values than the injury threshold.

<Table 6> Simulation results of the minivan

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
Minivan	Compact vehicle	10	3.42	2.50
		15	5.18	3.74
		20	6.89	4.98
		25	8.60	6.25
	Medium-sized vehicle	10	4.34	2.83
		15	6.51	4.24
		20	8.67	5.71
		25	10.83	7.10
	SUV	10	4.96	3.05
		15	7.43	4.54
		20	9.90	6.02
		25	12.39	7.04
	Minivan	10	4.96	2.99

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
		15	7.46	4.50
		20	9.96	5.98
		25	12.44	7.04
	Small truck	10	5.55	3.28
		15	8.31	4.92
		20	11.06	6.44
		25	13.81	7.21

Note: The shaded cells show higher values than the injury threshold.

8. Simulation Results of the Small Truck used as the Rear-ended Vehicle

The occupants in the small truck used as the rear-ended vehicle will like to sustain a whiplash injury when the compact and medium-sized vehicles weighing lighter than the small truck collide at a speed of 25 km/h (<Table 7>). However, the occupants are highly possible to sustain an injury when a vehicle of 1,000 kg or higher collides at a speed of 20 km/h or higher.

<Table 7> Simulation results of the small truck

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
Small truck	Compact vehicle	10	2.84	2.03
		15	4.38	2.98
		20	5.49	4.02
		25	7.01	5.04
	Medium-sized vehicle	10	3.76	2.28
		15	5.71	3.43
		20	7.63	4.64
		25	9.53	5.64
	SUV	10	4.39	2.56
		15	6.64	3.84
		20	8.86	5.10
		25	11.09	5.64
	Minivan	10	3.75	2.43
		15	6.10	3.73
		20	8.37	5.04
		25	10.60	5.62
	Small truck	10	4.89	2.71
		15	7.35	4.03
		20	9.87	5.33
		25	12.40	5.61

Note: The shaded cells show higher values than the injury threshold.

Ⅴ. Result Comparisons Between The Vehicles Having The Same Weight

<Table 8> shows the simulation results of the collisions between the vehicles having the same weight. The speed change value is close to the injury threshold at a speed of 15 km/h when the threshold is based on the delta-V. The whiplash injury is highly possible for occupants in the rear-ended vehicle colliding at a speed of 20 km/h or higher. The injury is also highly possible at collisions with an impact acceleration of 15 km/h or higher. Therefore, the occupants in the rear-ended vehicle will highly sustain a injury when the collision speed is 15 km/h or higher in collisions between vehicles with the same weight. Moreover, the impact acceleration in the same collision speed decreases as the vehicle weight increases.

<Table 8> Results in rear-end collisions between the vehicles having the same weight

Rear-ended vehicle	Rear-ender vehicle	Collision speed in km/h	Simulation results	
			Delta-V in km/h	Collision acceleration in g
Compact vehicle	Compact vehicle	10	4.91	4.24
		15	7.39	6.19
		20	9.86	8.42
		25	12.33	10.41
Medium-sized vehicle	Medium-sized vehicle	10	4.98	3.41
		15	7.46	5.13
		20	9.93	6.83
		25	12.39	8.54
SUV	SUV	10	4.89	3.19
		15	7.43	4.51
		20	9.90	5.98
		25	12.37	7.01
Minivan	Minivan	10	4.96	2.99
		15	7.46	4.50
		20	9.96	5.98
		25	12.44	7.04
Small truck	Small truck	10	4.89	2.71
		15	7.35	4.03
		20	9.87	5.33
		25	12.40	5.61

Note: The shaded cells show higher values than the injury threshold.

1. Relationship between the Collision Speeds and the Whiplash Injury Risk

The injury threshold is not met at a collision speed of 10 km/h, regardless of the associated vehicles' weight. However, most occupants in the rear-ended vehicle will likely sustain a injury at a collision speed of 25 km/h, regardless of the weight. Injury is also likely possible when the small truck used as the rear-ended vehicle collides with any vehicle at a speed of 15 km/h. The percentages of injury possibility are 0%, 36%, 84%, and 98% at collision speeds of 10, 15, 20, and 25 km/h, respectively, if the percentage is converted from the result of the collision speed.

2. Relationship between the Weights and the Whiplash Injury Risk

The injury possibility is higher for 14 of 64 scenarios when the events, where the leading vehicle is heavier than a vehicle behind, are compared. Injury is highly possible when the rear-ender vehicle is heavier than the rear-ended one. Therefore, the occupants are less likely to sustain an injury because of the lower speed variation and the impact acceleration when the weight of the rear-ended vehicle increases as presented in <Tables 9> and <Table 10>.

<Table 9> Simulation results of the collision speeds

Collision speed in km/h	Simulation results									
	Delta-V in km/h					Collision acceleration in g				
10	4.91	4.07	3.34	3.42	2.84	4.24	3.02	2.36	2.50	2.03
	5.84	4.98	4.23	4.34	3.76	4.50	3.41	2.90	2.83	2.28
	6.49	5.66	4.89	4.96	4.39	4.93	3.66	3.19	3.05	2.56
	6.49	5.64	4.94	4.92	3.75	4.81	3.83	3.04	2.99	2.43
	7.03	6.20	4.92	5.55	4.89	4.99	4.66	3.15	3.28	2.71
15	7.39	6.07	5.46	5.18	4.38	6.19	4.53	3.76	3.74	2.98
	8.78	7.46	5.07	6.51	5.71	6.83	5.13	4.11	4.24	3.43
	9.76	8.47	6.40	7.43	6.64	7.34	5.53	4.51	4.54	3.84
	9.73	8.43	7.43	7.46	6.10	7.19	5.57	4.54	4.50	3.73
	10.55	9.28	8.22	8.31	7.35	7.44	6.38	4.62	4.92	4.03
20	9.86	8.07	6.75	6.89	5.49	8.42	6.07	4.96	4.98	4.02
	11.73	9.93	8.53	8.67	7.63	9.41	6.83	5.49	5.71	4.64
	13.07	11.27	9.90	9.90	8.86	9.70	7.33	5.98	6.02	5.10
	12.96	11.21	9.89	9.96	8.37	9.63	7.39	6.12	5.98	5.04
	14.03	12.35	10.98	11.06	9.87	9.94	7.73	6.24	6.44	5.33
25	12.33	10.05	8.43	8.60	7.01	10.41	7.95	6.03	6.25	5.04
	14.67	12.39	10.68	10.83	9.53	11.67	8.54	6.83	7.10	5.64
	16.20	14.06	12.37	12.39	11.09	11.89	9.14	7.01	7.04	5.64
	16.18	13.98	12.39	12.44	10.60	11.99	9.26	7.42	7.04	5.62
	16.85	15.39	13.69	13.81	12.40	12.04	9.76	7.17	7.21	5.61

Note: The shaded cells show higher values than the injury threshold.

<Table 10> Simulation results of the vehicle weights

Rear-ended vehicle	Rear-ender vehicle	Speed	Result									
			Delta-V in km/h				Ave.	Acceleration in g				Ave.
+500 kg		10	4.07	4.23	4.96	3.75	4.25	3.02	2.90	3.05	2.43	2.85
		15	6.07	6.40	7.43	6.10	6.50	4.53	4.11	4.54	3.73	4.23
		20	8.07	8.53	9.90	8.37	8.72	6.07	5.49	6.02	5.04	5.66
		25	10.05	10.68	12.39	10.60	10.93	7.95	6.83	7.04	5.62	6.86
+1,000 kg		10	3.34	4.34	4.39		4.02	2.36	2.83	2.56		2.58
		15	5.07	6.51	6.64		6.07	3.76	4.24	3.84		3.95
		20	6.75	8.67	8.86		8.10	4.96	5.71	5.10		5.26
		25	8.43	10.83	11.09		10.12	6.03	7.10	5.64		6.26
+1,500 kg		10	3.42				3.42	2.50				2.50
		15	5.18				5.18	3.74				3.74
		20	6.89				6.89	4.98				4.98
		25	8.60				8.60	6.25				6.25
	+500 kg	10	5.84	5.66	4.94	5.55	5.50	4.50	3.66	3.04	3.28	3.62
		15	8.78	8.47	7.43	8.31	8.25	6.83	5.53	4.54	4.92	5.46
		20	11.73	11.27	9.89	11.06	10.99	9.41	7.33	6.12	6.44	7.32
		25	14.67	14.06	12.39	13.81	13.73	11.67	9.14	7.42	7.21	8.86
	+1,000 kg	10	6.49	4.94	5.55		5.66	4.93	3.04	3.28		3.75
		15	9.76	7.43	8.31		8.50	7.34	4.54	4.92		5.60
		20	13.07	9.89	11.06		11.34	9.70	6.12	6.44		7.42
		25	16.20	12.89	13.81		14.13	11.89	7.42	7.21		8.84
	+ 1500 kg	10	5.64				5.64	3.83				3.83
		15	8.43				8.43	5.57				5.57
		20	11.21				11.21	7.39				7.39
		25	13.98				13.98	9.26				9.26

Note: The shaded cells show higher values than the injury threshold.

Ⅵ. Conclusion And Future Research

This study applies the MADYMO software to simulate rear-end collisions at low speeds. A total of 100 scenarios are set to simulate the collisions based on the different rear-ended and rear-ender vehicle weights and various collision speeds of the rear-ender vehicle. The total weight is categorized based on the weights of the compact and medium-sized vehicles, SUV, minivans, and small trucks, including vehicle occupants and loads. The collision speed is changed from 10 km/h to 25 km/h for low-speed, rear-end collisions. The thresholds of the delta-V and collision acceleration in the rear-ended vehicle are set to 8 km/h and 5g, respectively, based on previous studies to identify the injury possibility. Sustaining injury is highly possible for the occupants of the rear-ended vehicle when the vehicles with the same weight collide at a speed of 15 km/h or higher. The impact of acceleration decreases when the vehicle weights increase. When the vehicle weights are disregarded, the risk of injury becomes 0%, 36%, 84%, and 98% at collision speeds of 10, 15, 20, and 25 km/h, respectively, given that a percentage is converted from the result of the speed change and collision acceleration. The results of the situation, where both vehicles stopped to end after crashing in rear-end collisions, have been obtained in this research.

However, an offset collision is more likely to occur in reality among rear-end collisions associated with constraints, such as stopping at traffic signals. The speed change and collision acceleration of the rear-ended vehicle are expected to change in the offset collision. Moreover, the collision result could be different if the driver of the rear-ender vehicle realizes that he/she is colliding and reduces speed. Therefore, future research is needed to include various collision types. Realistic rear-end collisions are affected by other factors, such as the occupant's seat belt-wearing attitude, seat positions, and safety restraints, which are also related to occupants with a seat and a headrest. However, this study still estimates the injury possibility and compares this to the injury threshold of the speed change and collision acceleration from the rear-ended vehicle. Future research is needed to reflect those factors. This research investigates how the weights of two vehicles and collision speeds affect the possibility of whiplash injury when the occupants are in the rear-ended vehicle. These results are expected to contribute to a foundation of developing alternatives to reduce societal costs brought about by moral hazard in minor traffic accidents.

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