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VERIFICATION AND COMPLEMENT OF EDR SPEED DATA THROUGH THE ANALYSIS OF REAL WORLD VEHICLE COLLISION ACCIDENTS

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ABSTRACT−In this paper, two methods for practical verification and complementation of speed data stored in EDR are presented. Both methods are based on analyses of actual collision accidents and can be performed in parallel with conventional accident analysis procedure. One of the two methods uses video footage stored in vehicle-mounted camera (black box) to estimate the speed of vehicles. The other method is for performing optimal analysis based on vehicle collision model built in the range of rigid body dynamics. Through analyses of black box footage from actual collision accidents, it was confirmed that the estimated speed matched the data stored in EDR with high accuracy. Additionally, by using actual collision cases, the practicality of vehicle collision model-based speed estimation method was validated. In cases where video footage is not available, optimization method based on rigid body collision model can be used together with EDR data.

KEY WORDS : Event data recorder, Vehicle speed, Verification and complement, Vehicle-mounted camera (black box), Rigid-body impact, Accident reconstruction

1. INTRODUCTION

In recent times, accident analyses using even data recorders (EDR) (Vandiver *et al*., 2015; Bortles *et al*., 2016) are performed to resolve uncertainty issues in the field of accident reconstruction. However, it is not yet possible to obtain intact EDR data of all vehicles involved in an accident, as vehicles without an EDR may be involved or the data may be lost due to the collision. Additionally, despite the previous researches (Ruth and Tsoi, 2014; Tsoi *et al*., 2014) on EDR data accuracy, it is difficult to say that the validation of various EDR data of many vehicles is sufficiently secured.

This study suggests two practical verification and complementation methods for EDR speed data. Both methods are based on analyses of actual collision accidents and can be applied in parallel with the conventional vehicle accident analysis process.

The first method involves using video footage stored in a vehicle-mounted camera (black box) to estimate the speed of vehicles involved in an accident (Han, 2016). This method uses projection transformation and cross ratio, calculating the distance traveled by the vehicle based on the video footage including certain objects, and eventually obtains the estimated car speed. Specification of the location of the vehicle through video footage is not required with this method. In cases where EDR speed data of all vehicles involved in the accident is available, this method can be used to verify the reliability of the EDR data. When these verification processes are done multiple times, the reliability of EDR for many vehicles can be verified without additional work or cost. In addition, it is possible to estimate the speed of a vehicle without an EDR at a level close to that of the EDR equipment.

With the second method, optimization analysis based on collision model (Han, 2015) is performed when any of the vehicles involved in the collision does not have an EDR or when the data is incomplete, to calculate the approximate pre- and post-collision speed of both vehicles (Brach and Brach, 2015; Han, 2018). This method could potentially be applied to the analysis of vehicle collision accidents that have not acquired video footage as well as EDR data. Even when all EDR data can be secured, using this method verifies the reliability of data.

With five collision accident cases provided by the National Forensic Service (NFS) of Korea and the related video footage stored in the black box, their data was analyzed and each time frame was compared with the speed data stored in the EDR. The accident cases were chosen with preference of those involving very fast or slow speeds or extreme changes in speed. It was confirmed that video analysis and EDR data could be used together in most cases. With another three collision cases provided by the NFS, the practicality of the collision model-based methods proposed in this paper was confirmed. Through case studies, these methods were found to be useful not only for collisions involving vehicles with EDR, but also when the EDR data is partially lost. From this information,

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it can be concluded that optimization analysis methods based on rigid body collision model can be applied with EDR data when no video footage is available.

2. BLACK BOX FOOTAGE ANALYSIS AND VEHICLE COLLISION MODEL

In this section, two methods for reconstructing collision speed, the most important information in a collision accident analysis, are shown. The first method uses the black box footage, and the other method uses optimization analysis based on vehicle collision model.

2.1. Vehicle Speed Estimation Based on Video Footage Analysis

The conventional method used for estimating the speed of vehicles involved in an accident from black box footage includes measuring the distance between certain immobile objects shown in the footage and the time it takes the vehicle to pass through that distance. When it is not possible to find immobile objects or landmarks to specify the location of the vehicle, speed estimation can be impossible or the accuracy is lowered. Unlike the conventional method, this study used projective transformation and cross ratio to find the relationship between the distance seen in the video footage and the actual distance of certain objects to calculate the travel distance of the vehicle and its speed. A brief description of the method used in this study is provided here. A detailed explanation can be found in the author's previous research (Han, 2016).

Blackbox footage containing the accident can be interpreted using projective transformation, and the cross ratio should be the same. By superimposing a screenshot of the footage containing the desired vehicle movement on another screenshot after a short period of time (Δt) where the vehicle has moved a distance of $d = (BD) = (AC)$, it results in an image as shown in Figure 1. If the movement of the vehicle is linear, the cross ratio of the four points marked in Figure 1 (A, B, C, D) can be calculated. With the nonconformity ratio calculated from these images, and the lengths of (AB) and (CD) which corresponds to the wheel base (l), The travel distance d at time interval Δt can be obtained as shown in Equation (1), enabling the estimation of the speed.

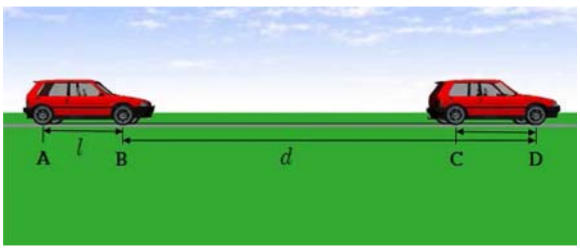

Figure 1. Application of cross-ratio method for estimation of a vehicle speed (Han, 2016).

$$d = \sqrt{\frac{\{A'B',\, C'D'\}}{\{A'B',\, C'D'\}-1}} \cdot l \qquad (1)$$

where

$$\{A'B',\, C'D'\} = \{AB,\, CD\} = \frac{d^2}{(d+l)(d-l)} = \frac{d^2}{d^2-l^2}$$

With the conventional method, the speed is usually calculated using more than 10 m of travel distance, which is not suitable for estimating the speed for a short travel distance during collision where there are extreme changes in the speed.

To estimate the speed of the recording vehicle with its recorded footage based on cross ratio, non-moving objects with measurable length (distance) should be used as reference. Street lights, trees, or lane markings with constant space between them are good examples, but any fixed object can be used.

2.2. Vehicle Collision Analysis Based on Rigid Body Dynamics

The impact diagram shown in Figure 2 is based on the principle of impulse and momentum, and as for the constraints at the equivalent impact point which can be considered as the impact center, coefficient of restitution was applied for the normal direction and impulse ratio for the tangential direction. Details of the rigid body collision model can be found in the author's previous study (Han, 2015).

In Figure 2, P_n and P_t are the normal and tangential impulses acting on vehicle 2, respectively. The same magnitude of impulses from the opposite direction acts on vehicle 1. The analytical expression of the impulses can be obtained with equations based on the principle of impulse and momentum, the coefficient of restitution e, and the impulse ratio μ_r defined by the ratio of the normal impulse to the tangential impulse.

For the verification of optimization, the speed data of

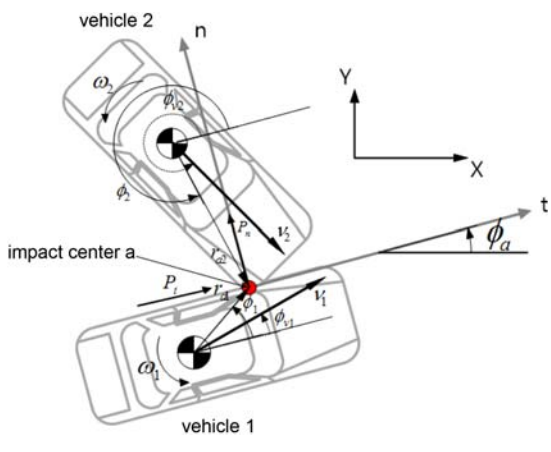

Figure 2. Diagram of planar rigid-body impact of vehicles (Han, 2015).

vehicles with EDR before the collision are used as true values in case of two-vehicle collision. Through repeated process of minimizing the difference between the post-collision speed obtained using rigid body collision model and the pre-collision speed data from EDR, and the post-collision data stored in the EDR, making it possible to estimate both pre- and post-collision speed of the vehicle without EDR. The minimum difference between the post-collision speed of the EDR-mounted vehicle calculated with rigid collision model and the value ε obtained from the EDR data was defined as Equation (2). In Equation (2), superscript *data* denotes EDR data and subscripts t and n denote tangential and normal direction, respectively.

$$\varepsilon = \frac{1}{2}m(V_t - V_t^{data})^2 + \frac{1}{2}m(V_n - V_n^{data})^2 + \frac{1}{2}I(\omega - \omega^{data})^2 \qquad (2)$$

The *n-t* coordinate system is essential for repetitive calculations of the impulse-momentum equations during the optimization process, although the EDR data will not be recorded in the coordinate system. In addition, the last term of Equation (2) is excluded when the EDR data does not include the angular speed (ω^{data}).

3. BLACK BOX FOOTAGE ANALYSIS: PRE-COLLISION SPEED

With collision accident cases provided by the NFS and the previous described projective transformation and cross ratio, pre-collision speed was calculated and compared with the EDR data. Cases were chosen among those with extreme speeds or large differences, and it was confirmed that the video analysis results and EDR data corresponded to each other well. However, based on studies of EDR speed data of major vehicles driven in the North America (Ruth and Tsoi, 2014; Tsoi *et al*., 2014), when highly accurate tools are used to measure speeds in elaborately constructed collision tests, pre-collision speeds had an error range of 4 %, while speed change ΔV related to post-collision speed had an error range of 10 ~ 20 %.

3.1. Hyundai Sonata

In this accident case, a Hyundai Sonata is accelerated from a stationary position, resulting in frontal-collision with the edge of a wall. As shown in Table 1, relatively low speed is recorded in EDR as the car was accelerated from a still position. In this case, even though EDR-recorded speed is low, the error range of the estimated speed using black box footage analysis does not exceed approximately 10 %.

3.2. Hyundai Santa Fe

This case involves Santa Fe (Sport Utility Vehicle, SUV) which rapidly accelerated and collided with multiple vehicles. Its speed increases during the stored time interval. The speed before the first collision was estimated with the black box footage and compared with EDR data, as shown in Table 2. As shown in Table 2, the pre-collision speeds estimated with black box footage analysis and EDR data correspond to each other well, indicating these two types of data can be applied together.

Table 1. Hyundai Sonata pre-collision speed data: EDR and black box.

Before collision (s)	EDR (km/h)	Black box (km/h)	% diff
− 5	0	0	-
− 4.5	0	0	-
− 4	0	0	-
− 3.5	2	0	-
− 3	10	11	10.0
− 2.5	14	13.3	− 5.0
− 2	18	18.6	3.3
− 1.5	21	22	4.8
− 1	26	28.1	8.1
− 0.5	31	35.1	13.2

Table 2. Hyundai Santa Fe pre-collision speed data: EDR and black box.

Before collision (s)	EDR (km/h)	Black box (km/h)	% diff
− 5	89	86.9	− 2.4
− 4.5	92	91.7	− 0.3
− 4	97	91.7	− 5.5
− 3.5	99	97.1	− 1.9
− 3	102	103.1	1.1
− 2.5	107	103.1	− 3.6
− 2	109	110	0.9
− 1.5	111	108.3	− 2.4
− 1	116	117.9	1.6
− 0.5	117	117.9	0.8

3.3. Hyundai Tuscon

In this accident, medium-sized SUV Tucson rapidly accelerated and collided with a traffic pole and a tree. The EDR data right before the collision (– 0.5 s) is shown as "Invalid data or Not Supported". Even with the high speed of the vehicle and large changes in speed, the difference between EDR data and footage analysis was within 4 %, which indicates the two types of data correspond to each other.

3.4. GM (Chevrolet) Orlando

In this accident, a medium-sized SUV Orlando which was

Table 3. Hyundai Tuscon pre-collision speed data: EDR and black box.

Before collision (s)	EDR (km/h)	Black box (km/h)	% diff
− 5	86	88.7	3.1
− 4.5	90	88.7	− 1.4
− 4	94	90.4	− 3.8
− 3.5	94	90.6	− 3.6
− 3	96	97.6	1.7
− 2.5	98	100.7	2.8
− 2	100	97.6	− 2.4
− 1.5	103	100.7	− 2.2
− 1	108	111.6	3.3
− 0.5	-	57.4	-

Table 4. GM (Chevrolet) Orlando pre-collision speed data: EDR and black box.

Before collision (s)	EDR (km/h)	Black box (km/h)	% diff
− 5	16	15.8	− 1.3
− 4.5	17	15.8	− 7.1
− 4	18	18.5	2.8
− 3.5	19	18.5	− 2.6
− 3	20	21.1	5.5
− 2.5	23	21.1	− 8.3
− 2	27	25.3	− 6.3
− 1.5	35	39.5	12.9
− 1	42	42.2	0.5
− 0.5	49	48.6	− 0.8

traveling slowly, then accelerated and collided into a standing truck. The acceleration of the SUV is relatively high in this case. As shown in Table 4, during the time frame recorded by the EDR, the error range of the speed obtained via video analysis is within approximately 10 %.

3.5. GM (Chevrolet) Trax

In this accident, the mini-SUV Trax maintains a very high speed during the time frame recorded by the EDR, excluding the momentary acceleration and deceleration. As shown in Table 5, the difference between EDR speed data and the black box footage analysis data is less than 10 %. However, since the video footage becomes extremely shaky near the colliding moment, the error range of the estimated speed in that time frame resulted wider than others.

Table 5. GM (Chevrolet) Trax pre-collision speed data: EDR and black box.

Before collision (s)	EDR (km/h)	Black box (km/h)	% diff
− 5	107	108.1	1.0
− 4.5	109	108.1	− 0.8
− 4	112	113.3	1.2
− 3.5	116	123.6	6.6
− 3	103	108.1	5.0
− 2.5	100	99	− 1.0
− 2	92	88.1	− 4.2
− 1.5	95	88.2	− 7.2
− 1	94	88.2	− 6.2
− 0.5	122	113.3	− 7.1

4. VEHICLE COLLISION MODEL: PRE-AND POST-COLLISION SPEED

With three collision accident cases (Han, 2018) provided by the NFS in which EDR is only mounted on one vehicle, estimation of collision speed using previously described collision model was done. The estimated speed of non-EDR-mounted vehicle was compared with the value obtained through black box footage analysis, establishing the effectiveness of the collision model used in this study. In other words, it shows that the EDR data of the vehicle is comparable to the results of the collision model optimization analysis as well as the results of the black box video analysis. When there is loss or lack of footage needed for speed calculation, using the vehicle collision model could be a useful solution.

4.1. Collision accident of Orlando SUV and Truck

In this case, a rapidly accelerating Orlando SUV collided into the rear of the truck standing still on a red light. Only

Table 6. Orlando SUV and truck: Pre-/post-collision speed data.

		Black box	EDR	Impact model
Orlando	Pre-collision speed (km/h)	52	54	54
	Post-collision speed (km/h)	28	26	26
Truck	Pre-collision speed (km/h)	0	-	0
	Post-collision speed (km/h)	12	-	12

the Orlando had an EDR. Table 6 summarizes the estimations for pre- and post-collision speed, and the post-collision speed of the truck based on the optimization work based on collision model matches quite accurately with the results from black box footage analysis performed using nonconformity ratio. This indicates that pre- and post-collision speed calculated through optimization of collision model is comparable with EDR data.

Additionally, Table 6 shows that optimization of collision model can compensate for loss or lack or EDR data.

4.2. Collision accident of Avante and Truck

This case involves an Avante, which slipped during travel and went across the centerline, then collided with a truck traveling the opposite direction. Optimization of collision analysis was performed based on the EDR of the Avante. In this accident, there was no data for the pre- and post-collision speed of the truck, and the EDR data for the post-collision speed (difference in velocity ΔV) of the Avante was also lost.

As shown in Table 7, optimization results closely match the black box footage analysis results.

4.3. Collision accident of SM5 and Spark

In this accident, a compact car Spark crossed the centerline and collided with an SM5 sedan traveling in the opposite direction. There is no video footage available for this accident, but since the SM5 had an EDR, collision model optimization was performed to estimate the pre- and post-collision speed of Spark as shown in Table 8. The estimated pre- and post-collision speed of SM5 was close to that of NFS analysis results (43 km/h) (Park, 2015), and it was concluded that even though there is no way to verify the accuracy of the estimated post-collision speed, the collision model analysis yielded acceptable results.

Table 7. Avante and truck: Pre-/post-collision speed data.

		Black box	EDR	Impact model
Avante	Pre-collision speed (km/h)	71	71	71
	Post-collision speed (km/h)	25	Lost	25
Truck	Pre-collision speed (km/h)	63	-	57
	Post-collision speed (km/h)	29	-	22

Table 8. SM5 and Spark: Pre-/post-collision speed data.

		Black box	EDR	Impact model
SM5	Pre-collision speed (km/h)	-	43	43
	Post-collision speed (km/h)	-	25	25
Spark	Pre-collision speed (km/h)	-	-	52
	Post-collision speed (km/h)	-	-	20

5. CONCLUSION

In this paper, two methods of verification and complementation of EDR-stored speed data, based on actual accidents, were proposed. The first method involves estimating the vehicle speed using the video footage stored in black box. Projective transformation and cross ratio are used, which enables relatively certain calculation of vehicle speed by obtaining the travel distance with the ratio between the size of still objects visible in the footage and the actual size of the same objects. The second method can be applied in accidents involving vehicles without EDR, estimating the pre- and post-collision speed of non-EDR-mounted vehicle using the corresponding values of EDR-mounted vehicle. This method involves optimization analysis based on the vehicle collision model (Han, 2015) within the field of rigid-body dynamics developed by the author.

Through the analysis of black box footage of five collision cases provided by NFS, the estimated values were compared with the EDR data. The cases were chosen based on the extremes or large differences of vehicle speeds, and it was confirmed that footage analysis and EDR data corresponded to each other well enough to be used together in most cases. Additionally, with three collision cases provided by the NFS, the collision model-based speed estimation methods developed in this study were verified. With case studies, it was confirmed that the proposed methods were still valid when non-EDR-mounted vehicles were involved. When video footage of the accident is not available, optimization analysis based on rigid body collision model can be used along with EDR data.

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