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# Vehicle Speed Measurement Methodology Robust to Playback Speed-Manipulated Video File

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**ABSTRACT** Concomitant with the virtual ubiquity of dashcams in vehicles, the instantaneous speed of vehicles during accidents can now be measured using dashcam videos to understand the causes of such accidents. In this study, we estimated vehicle speeds using dashcam videos recorded in various road environments and analyzed them by comparing them to ground truth. We also considered various scenarios yielding retaken and re-encoded videos from additional recording devices, depending on the circumstances, wherein the original video can be manipulated in terms of playback speed and/or frames per second. The experimental results revealed that the actual and measured speeds were similar for most user-specific intervals. Moreover, the results suggest that our estimated speed is adequately valid as evidence, regardless of retake and re-encoding states. Furthermore, we adopted a statistical approach (i.e., Pearson's correlation coefficient analysis) to verify the proposed vehicle speed estimation method. The results showed that when playback speed was manipulated in re-encoded or retaken video, the proposed method consistently measured speeds at 99.99 % accuracy. This verified method will play an important role in deriving reliable results from various evidential video sources.

**INDEX TERMS** Dashcam, retake, re-encoded video, vehicle speed measurement, video forensic, video manipulation.

## I. INTRODUCTION

Upon the occurrence of a traffic accident, the speed of the vehicle prior to collision is considered as important for determining the root cause of the accident and for investigating the responsibilities among interested parties [1]. Typically, the investigator presumes the vehicle speed based on the statements of drivers, who were involved or had witnessed the accident, owing to the lack of objective evidence. Nevertheless, the statements of drivers or witnesses cannot be deemed acceptable as such statements are heavily dependent on their memory and drivers can tort relevant information. Therefore, vehicle speeds are required to be captured using objective devices (i.e., event data recorders (EDRs), tachometers, and/or video footage).

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Data from EDRs in airbag control units and digital tachographs are commonly used to make these determinations. Unfortunately, EDRs can sometimes provide unreliable data if the impact of the collision is more significant than the threshold (i.e., airbag deployment) [2]. Although the digital tachograph constantly logs vehicle speed, its use is primarily restricted to commercial vehicles, such as buses and trucks.

Recently, several studies have proposed methods to overcome this limitation by adopting video sequences [3]. For instance, vehicle speed estimation methods using closed-circuit television (CCTV) or automobile black box devices on the dashboard (i.e., dashcams) constitute the most fundamental approaches [1], [3]. Additionally, CCTV videos have been used in many studies to estimate vehicle speeds by tracking vehicle movements from fixed locations [4]–[8].

Generally, CCTV cameras are fixed and cover a large area at an instant and, thus, recorded objects including vehicles are

indistinguishably small with relation to each other. Additionally, light reflections from headlights and streetlights at night tend to hinder analysis.

The dashcam is mounted on the dashboard of a vehicle to record videos while driving, thereby providing better visibility in terms of the shorter distance between the viewer's perspective and the front of the car; plus, it is more robust with illumination than CCTVs [9]. Recently, an increasing number of drivers have used dashcams for evidence purposes [10]. Thus, the requirement of speed estimation using dashcams has become essential, and it is widely used in situations related to accidents [11]. Several studies have measured vehicle speeds using dashcam videos [12]–[16]. However, most did not consider weather conditions [17]. Other studies have examined the problem of video manipulation when videos are used as evidence [18], [19]. From this perspective, researchers have considered numerous evidence-collection situations (e.g., re-recording videos from a display during playback or re-encoding videos for internet transmission). Nonetheless, the validation of the proposed vehicle speed estimation methods has not considered the distinction between originals, retakes, and re-encoded versions. Therefore, in addition to vehicle speed estimation, dashcam videos must be verified as authentic.

Therefore, we categorize dashcam videos into the following three types based on the acquisition method as original, retake, and re-encoded (as illustrated in Fig. 1). Original videos are those directly extracted from the storage attached to the dashcam. Retake videos are those recorded from the playback using another device. Re-encoded videos are those obtained from internet transmissions via e-mail or other means.

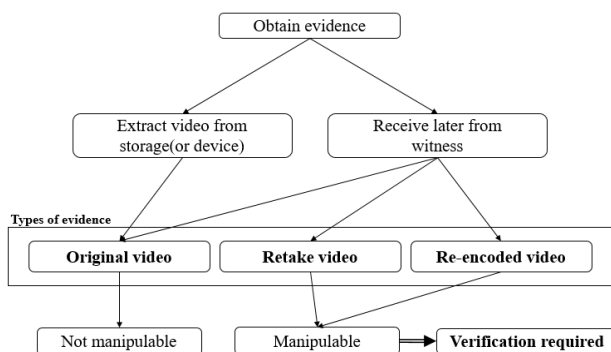


FIGURE 1. Types of collected videos.

Generally, applications automatically re-encode video files for transmission to reduce file size. When a party submits a retaken or re-encoded video, an investigator may not be able to accurately measure the speed based on information loss or tampering. Most extant studies have measured vehicle speeds from original video. Hence, we extend the conventional vehicle speed measurement method to provide verification of retaken and re-encoded videos.

This study proposes a robust methodology that can accurately measure vehicle speeds regardless of the edited playback speed, frames per second (fps), etc. in the submitted video. The methodology comprises detection and estimation phases. During the detection phase, we determine the real playback speed using optical character recognition (OCR) to compare the time and fps presented in the video to a real chronometer. During the estimation phase, vehicle speeds are measured by fps, and distance is measured using a satellite map.

Experiments show that when playback speed is manipulated in re-encoded and retaken videos at  $0.5\times$ , conventional methods estimate vehicle speeds at around 50 % of their actual speeds. This makes intuitive sense. With our proposed method, the actual speed is preserved with 99.99 % accuracy. Hence, our model is robust to editing manipulations.

The main contributions of this study can be summarized as follows.

- *Recognition of Playback Speed Alteration Impact:* We validate that video playback speed manipulation results in alterations to estimated vehicle speeds.
- *Robust Measurement of Vehicle Speed in Any Situation:* Our real playback speed detection method can be easily applied to conventional methods to accurately measure vehicle speeds.
- *Verification of the Proposed Method:* Experimental results verify the accuracy of our proposed strategy in all types of environments.

The remainder of this paper is organized as follows. Related work and the problems addressed in this study are detailed in Section II. The proposed vehicle speed measurement method using dashcam videos is described in Section III. Section IV presents the experimental results of real and estimated speeds obtained from original dashcam videos compared under various environments. Subsequently, the results of measured speeds based on retaken and re-encoded videos are compared with our proposed method and the conventional method. Finally, the conclusions of this study are presented in Section V.

## II. RELATED WORK AND PROBLEM STATEMENT

### A. RELATED WORK

In past research, vehicle speeds were estimated by measuring the number of moving frames and the changed distances between vehicles in a video.

Wong *et al.* [4] proposed a vehicle speed estimation method that leveraged cross-ratios from stationary surveillance camera (e.g., CCTV) recorded video without designating the precise configuration of vehicles and cameras. Edelman *et al.* [5] presented a method for estimating vehicle movement by reconstructing three-dimensional data from CCTV videos. Similarly, other studies suggested video-processing techniques for estimating traveling path and speed by detecting specific locations or the entire scenario [18]–[23]. Murashov and Stroganov [24] produced a method of estimating vehicle

speeds based on vision technologies from a fixed monocular CCTV video of a road. Lu *et al.* [25] proposed a method that used difference images to detect vehicle movement and distance. Other motion detection methods [26], [27] have been applied to estimate vehicle speeds from fixed locations. However, fixed-location cameras and CCTVs have problems with expanded areas, and they often have difficulty with lines and background features.

As mentioned above, dashcam methods have also been studied. Kim *et al.* [12] proposed a vehicle speed estimation method utilizing CCTV and extended it to dashcam videos. Han [13] proposed a vehicle speed estimation method using cross-ratios to dashcam videos, which is similar to Wong *et al.*'s method. The method was verified in several accident situations, and the results were compared to speeds measured by Global Positioning System (GPS) devices.

Moreover, most dashcams log GPS information that can conveniently provide vehicle data for very accurate speed acquisition. However, GPS signals can become unreliable in certain terrains and in cities. Li and Liu [14], Yamaguchi *et al.* [15] and Osamura *et al.* [16] suggested the use of additional information, such as vehicle acceleration data, to more accurately estimate vehicle speeds. However, the proposed methods cannot be applied to most cases because they require additional sensors.

Foremost, traditional vehicle speed measurement methods do not consider video manipulation techniques [17]–[19]. Hence, they do not overcome the veracity and reliability problems inherent in human testimony. In this paper we provide a robust method of accurately measuring vehicle speeds from dashcam video, even when manipulated.

## B. PROBLEM STATEMENT

In this study, we considered various situations in which investigators collect dashcam videos at the site of the accident, as illustrated in Fig. 1. For instance, the video is submitted separately after the accident in case it cannot be directly extracted from the dashcam or storage on site or can be played only with a dedicated viewer owing to digital rights management and privacy protection issues. In those situations, the videos must be offloaded and encoded. In other scenarios, someone may record the dashcam video playback using a smartphone in order to relay it to an e-mail recipient. This often requires re-encoding, segmenting, and/or file-size reductions for transmission.

Thus, the evidential videos can be classified into three types based on the abovementioned scenarios.

- *Type 1*: Original video is video directly viewed and/or extracted from the dashcam without secondary conversion. This is the most common evidentiary collection method. Because the original video has not been edited, it is possible to accurately measure the vehicle's speed using conventional methods.

- *Type 2*: Retake video pertains to a separate video recording of another video's playback. The original source is assumed to be trustworthy. However, during re-recording,

the playback speed can feasibly be changed, resulting in unreliable vehicle speed estimation.

- *Type 3*: Re-encoded video refers to video offloaded from the primary source device and converted for storage, playback, and/or transmission. As a result of compression and other encoding alterations, the accuracy of vehicle speed estimation cannot be guaranteed.

We measured vehicle speeds in a previous study [12] where the playback speed was altered to  $0.5\times$ ,  $0.7\times$ , and  $1.5\times$  the ground truth. These alterations are applicable to types 2 and 3 in this paper. The average speeds were measured at a distance of 333 m in a highway environment. As shown in Table 1, the average vehicle speed measured based on wheel speed was 77.78 km/h.

**TABLE 1. Difference of average speeds according to playback speed.**

Playback Speed	Estimated Speed (km/h)	Real Speed (km/h)	Difference (errors relative to real speed) (km/h)
$0.5\times$	37.78	77.78	- 40.00
$0.7\times$	53.00		- 24.78
$1.0\times$ (type 1)	75.70		- 2.08
$1.5\times$	113.62		+ 35.84

When the playback speed is  $0.5\times$ ,  $0.7\times$ , or  $1.5\times$ , it can be seen that the measured vehicle speed is significantly altered. Therefore, resolving and interpreting an accident scene becomes challenging and untrustworthy under many technical scenarios. Although previous studies did well in investigating various approaches to measuring vehicle speeds, they did not consider cases of manipulated submissions. These factors provide the impetus for our research herein.

## III. PROPOSED METHOD

### A. OVERVIEW

In this paper, we propose a method that can robustly measure vehicle speeds from dashcam video while considering the video's manipulation in various situations (i.e., types 1, 2, and 3). The proposed method comprises a detection phase that determines whether the playback speed of the video is altered, and an estimation phase that calibrates and measures the speed from the previous step.

- *Detection Phase*: Detection of the playback speed by comparing the time information displayed on the video with the fps.

- *Estimation Phase*: Measurement of the actual speed of the vehicle using the dashcam video based on the playback speed detected in the previous phase.

The vehicle speed can be robustly obtained from the dashcam video using these two proposed steps, regardless of video editing.

Table 2 provides a summary of the notation used in the proposed method. The *fps*, *fds*, and *dps* are used to detect the actual playback speed, and  $F_i$ ,  $j$ ,  $t$ ,  $d$ , and  $s$  denote the frame



FIGURE 2. Examples of displayed time information in dashcam videos.

TABLE 2. Summary of notation used.

Notation	Meaning
$fps$	Frames per second ( $fps$ ) is the number of frames shown in the video per second based on the playback time.
$fds$	Frames per displayed second ( $fds$ ) is the number of frames shown in the video per second based on the displayed time. For a 1x video, $fps = fds$ ; if the video is not a 1x video (such as type 2 or 3 video), $fps \neq fds$ .
$dps$	Detected playback speed ( $dps$ ) refers to whether the playback speed is edited; it is calculated using $fps/fds$ . If the playback speed has not been edited, $dps$ is 1; otherwise, it is not 1.
$F_{i,j}$	Frame number at reference point. $F_i$ is the start reference point of the section and $F_j$ is the end reference point of the section
$t, t_{max}, t_{min}$	Measured time ( $t$ ) is calculated using the start ( $F_i$ ) and end ( $F_j$ ) reference points of the section. $t_{max}$ is the maximum time that can be measured in the section, and $t_{min}$ is the minimum time that can be measured in the section.
$d, d_{max}, d_{min}$	Measured distance ( $d$ ) is calculated using a satellite map. Given the distance error of the satellite map, $d_{max}$ is the measured distance plus error and $d_{min}$ is the measured distance minus error.
$s, s_{max}, s_{min}, s_{avg}$	Measured speed ( $s$ ) is calculated by using distance ( $d$ ) and time ( $t$ ). $s_{max}$ is calculated by using $d_{max}/t_{min}$ and $s_{min}$ is $d_{min}/t_{max}$ , and then $avg(s_{max}, s_{min}) = s_{avg}$ .

number, time, distance, and speed used for measurement during the estimation phase.

## B. DETECTION PHASE

During this step, the playback speed is detected using the time information recorded in the video based on the fact that the time information of the dashcam device is recorded in the general video.<sup>1</sup> As depicted in Fig. 2, time information is displayed in the actual video. Because editing the displayed time is immensely difficult and is time-consuming even when the video playback speed is manipulated, the precise playback speed can be detected with reasonable assurance by extracting the time information displayed in the video using the OCR technique [28]. Furthermore, because the time is recorded in the same font at the same position in the dashcam video,

<sup>1</sup>In this paper, we do not consider the case where there is no time information in the dashcam video because most dashcams display time information in the video.

the recognition rate is almost 100%. Therefore, the technique can be easily applied.

The time information extracted from the OCR technique is utilized for the  $fps$ , which is used to obtain the detected playback speed (see Eq. (1)).<sup>2</sup>  $fds$  denotes the number of frames accounted for in a second using the OCR. Dividing  $fds$  by the  $fps$  of the video gives the detected playback speed:

$$dps = \frac{fds}{fps}. \quad (1)$$

For example, if a video originally captured at 30 fps was edited at  $0.5 \times$  speed, the video would be viewed at 60 frames per displayed second. In this case,  $fds$  is 60 and  $fps$  is 30. Therefore, the  $dps$  can be calculated as two, which allows the correction of the manipulation speed when measuring the vehicle speed in the subsequent phase.

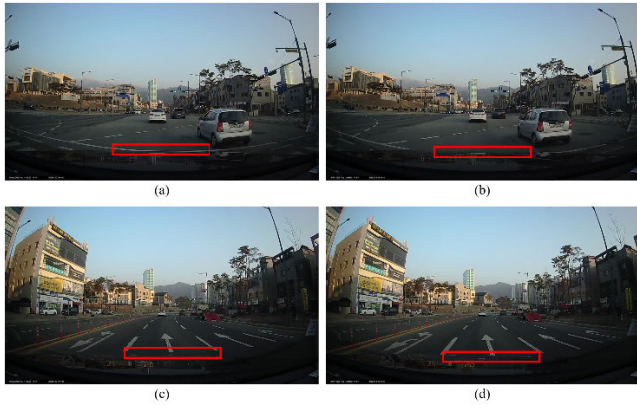
## C. ESTIMATION PHASE

Speed is measured by dividing distance by time [8], [12], [13], [29]. First, time  $t$  is calculated from the dashcam video by establishing a reference point for measurement. The video frames before and after passing the reference point is used. The dashcam cannot capture the moment at which the vehicle crosses the reference point of the section for speed measurement, because the dashcam does not record every instant, and a time gap occurs according to the fps.

Reference points can be specified using road marking (lanes, stop line, speed limits, zone markings, arrows, etc.). As presented in Figs. 3(a) and (b), the video frame number immediately prior to passing a white stop line with a red square as the start reference point is set as  $F_i$  (Fig. 3(a)), and reference point is set as  $F_{i+1}$  (Fig. 3(b)). Additionally, Figs. 3(c) and (d) display the video frame number immediately the video frame number immediately after passing the start before and after passing the tip of the white arrow marked with a red square as the end reference point:  $F_j$  and  $F_{j+1}$ , respectively.

The  $t_{max}$  covered by the vehicle in the area from the reference line depicted in Figs. 3(a) and (b) to that in Figs. 3(c) and (d) can be calculated by subtracting  $F_i$  from  $F_{j+1}$  and dividing it by the fps. Similarly, the  $t_{min}$  can be

<sup>2</sup>If the time information is up to the minute, the fps can be calculated by dividing the frames per displayed minute by 60.



**FIGURE 3. Frame selection for time measurement: (a) immediately before passing the reference point ( $F_i$ ); (b) immediately after passing the reference point ( $F_{i+1}$ ); (c) immediately before passing the end reference point ( $F_j$ ); (d) immediately after passing the end reference point ( $F_{j+1}$ ).**

calculated by subtracting  $F_{i+1}$  from  $F_i$  and dividing it by the fps. This is expressed in the following equation:

$$t_{max} = \frac{F_{j+1} - F_i}{fps}, \quad t_{min} = \frac{F_j - F_{i+1}}{fps}. \quad (2)$$

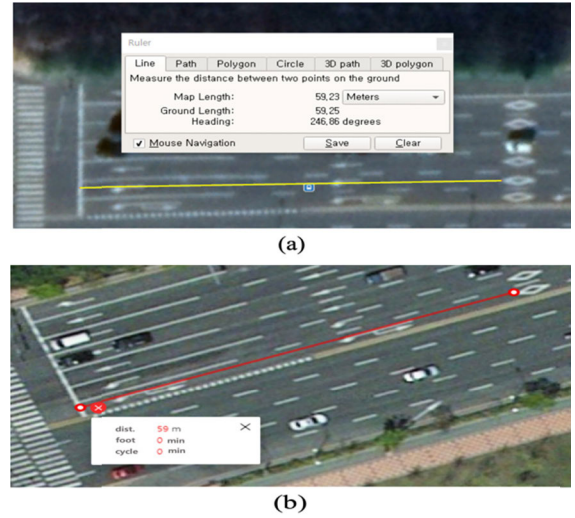
For instance, if  $F_i$  is the 10th frame,  $F_{i+1}$  is the 11th frame,  $F_j$  is the 50th frame,  $F_{j+1}$  is the 51st frame, and the fps is 30. The  $t_{max}$  required to travel from the start to end reference points can be evaluated as  $(51 - 10) / 30$ , which is approximately 1.37 s. Similarly, the  $t_{min}$  can be calculated as  $(50 - 11) / 30$ , which is approximately 1.3 s.

The distance,  $d$ , is measured using Google Earth satellite maps [30] and Kakao Map [31] as portrayed in Fig. 4. Although accurate results can be obtained if the actual distance is measured at the accident site, a satellite map is used because the actual distance cannot be measured at all locations and requires extensive measurement trials. Moreover, the error bound of satellite maps varies with region, but its accuracy is sufficiently high with the error at a centimeter scale, as confirmed in previous studies [32].

In this study, the range of the error ( $\delta$ ) is set to reflect the errors in satellites, inaccuracies in curved sections of roads, and mistakes that can occur during selection of a location on the map. This is derived in Eq. (3), wherein the  $d_{max}$  and  $d_{min}$  are calculated by adding and subtracting the errors to the values measured on the satellite map, as depicted in Fig. 4.

$$d_{max} = d + \delta, \quad d_{min} = d - \delta. \quad (3)$$

Finally, the speed,  $s$ , was derived from Eq. (4) by rewriting Eqs. (2) and (3). The  $s_{min}$  is calculated by dividing the  $d_{min}$  by the  $t_{max}$ , and conversely, the  $s_{max}$  is calculated by dividing the  $d_{max}$  by the  $t_{min}$ . Therefore, the speed is accurately calculated by considering the altered playback speed. The playback speed is corrected to  $1 \times$  by dividing the  $dps$  calculated in the previous phase. Moreover, because the unit of time in Eq. (2) is accounted in seconds, and the distance in Eq. (3) is considered in meters, the final speed is calculated by multiplying by the conversion factor of 3.6 to convert from m/s to km/h.



**FIGURE 4. Distance measurement with satellite map from (a) Google earth [30]. (b) Kakao map [31].**

The average value of the minimum and maximum speed can be derived as  $s_{avg}$ :

$$\begin{aligned} s_{min} &= \frac{d_{min}}{t_{max}} \times \frac{3.6}{dps} \\ s_{max} &= \frac{d_{max}}{t_{min}} \times \frac{3.6}{dps} \\ s_{avg} &= avg(s_{min}, s_{max}) \end{aligned} \quad (4)$$

#### IV. EXPERIMENTAL EVALUATION

In this section, we evaluate the performance of the proposed method for measuring vehicle speed robustly even with manipulated video. The variation in the real vehicle speed was identified from the odometer on the vehicle dashboard based on driving conditions. Subsequently, the measured speeds were compared to the speeds estimated from the dashcam videos for verification.

##### A. EXPERIMENTAL SETTING

To confirm the reliable speed measurement results, we used three types of data: the actual speed of the vehicle, the video extracted from the dashcam, and the video manipulated by retake and re-encoding.

The real speed of the vehicle was collected through the speedometer, as shown in Fig. 5. However, it is well known that vehicle speedometers have a tendency to display a speed higher than the real speed. Therefore, we considered this point and compared the actual speed with the measured speed.

The original type 1 video extracted directly from the dashcam was taken for file modeling (see Table 3). When the video was recorded with the default setting of the dashcam in Table 3, there were differences in resolution of  $2,560 \times 1,440$ ,  $1,920 \times 1,080$ , and  $1,280 \times 720$ , recoding at 30 fps and using an H.264/AVC codec.<sup>3</sup> The vehicle speed was

<sup>3</sup>The dashcam dataset can be found at [https://github.com/Kyu-Sun/Dashcam\\_manipulated\\_videos](https://github.com/Kyu-Sun/Dashcam_manipulated_videos)



FIGURE 5. Actual speed displayed on the speedometer.

TABLE 3. Dashcam models and specifications utilized in the experiment.

Model	Image resolution	fps	Recording duration	Video codec
iNavi Z500+	1,920×1,080	30	1 min	H.264/AVC
Eyeclone i5	1,920×1,080	30	1 min 16 s	H.264/AVC
FineVu LX2000	1,920×1,080	30	various	H.264/AVC
iROAD T8	1,280×720	30	1 min 30 s	H.264/AVC
Lead I K2	1,920×1,080	30	various	H.264/AVC
TopSync GQ800	2,560×1,440	30	30 s	H.264/AVC

measured from the videos recorded by six dashcams using the measurement method outlined in Section III, and it was compared to the real vehicle speed.

As a result of measuring the speed with the dashcam videos of the six models, there was no difference in the measured speed depending on the model. Hence, it can be seen that the resolution and recording duration, the only differences, did not affect the speed measurement. Since they are made for commercial purposes, the experiment results were not different as the video quality was sufficient to confirm the driving of the vehicle and time information.

As expressed in Eq. (4), distance and time comprise the parameters of speed, but distance is measured using the satellite map. Thus, there is no variation, unless the video data are not verified, owing to distortion. This study neglected a video if it had serious distortions and could not be used as evidence.

Time is significantly affected by variations in fps and playback speed, because the number of video frames is used as a factor of time measurement. Therefore, the measured time varies with the number of video frames recorded per second. Time is affected only by fps when the playback speed is 1×; otherwise, the time is influenced by the playback speed. Thus, the measured speed was validated based on variation of both the fps and playback speed. Afterwards, the video of the iNavi Z500+ model was used in the experiment with the original video corresponding to type 1.

We generated types 2 and 3 videos from the type 1 video to verify the measured speed for manipulated videos. To obtain type 2, type 1 was played using an ordinary video player (e.g., VLC [33] or Windows Media [34]), and the playback screen was recorded using a digital camera. The type 3 video was created using video editing software (e.g., Adobe Premier [35] and a smartphone messenger

application (e.g., WhatsApp [36] and Facebook messenger [37]). Thus, the video was re-encoded to reduce the file size and hence speed up its network transmission.

Notably, the resolution, fps, and playback speed of the types 2 and 3 videos were altered compared with those of type 1. Owing to these factors, the variations in fps and playback speeds influenced speed measurement.

Table 4 summarizes the files used in the experiment to evaluate the method proposed in this paper. Files #1 and #2 were dashcam videos of downtown and highway environments, respectively, in type 1 compared with the actual. Files #1 and #2 were original and were used as baselines in each experiment, and types 2 and 3 videos were made by re-encoding and retaking them. The playback speed varied with values of 0.5×, 0.7×, and 1.5×, and the fps varied with values of 10, 24, and 60.

TABLE 4. Video files used in the experiments.

File name.	fps	Playback Speed	Resolution	Road Type
file #1(downtown _original)	30	1x	1,920 ×1,080	Downtown
file #2(highway _original)	30	1x	1,920 ×1,080	Highway
file #3(downtown _0.5x_24fps)	24	0.5x	2,560 ×1,440	Downtown
file #4(highway _0.5x_24fps)	24	0.5x	1,920 ×1,080	Highway
file #5(highway _0.5x_30fps)	30	0.5x	1,280 ×720	Highway
file #6(highway _0.7x_30fps)	30	0.7x	1,280 ×720	Highway
file #7(highway _1.5x_30fps)	30	1.5x	1,280 ×720	Highway
file #8(highway _1x_10fps)	10	1x	2,560 ×1,440	Highway
file #9(highway _1x_24fps)	24	1x	1,920 ×1,080	Highway
file #10(highway _1x_60fps)	60	1x	1,920 ×1,080	Highway

Files #3–10 were types 2 and 3 videos. Files #3 and #4 had edited fps and playback speeds. File #3 was created using file #1, and file #4 was created using file #2. Files #5–7 reflected the changing playback speeds of file #2, and files #8–10 reflected the changing fps in file #2.

To determine whether the speed of the retake and re-encoded dashcam video was accurately measured, a comparison was made with VSEM [12], which measures the dashcam video speed with a methodology similar to that of the proposed technique.

## B. COMPARISON OF REAL AND MEASURED SPEEDS

### 1) SPEED VARIATION IN DRIVING ENVIRONMENT

The speed variation was reviewed by measuring the vehicle speed during driving on two roads: downtown and a highway. The speeds measured during driving downtown and on the highway for approximately a minute are presented in Fig. 6.

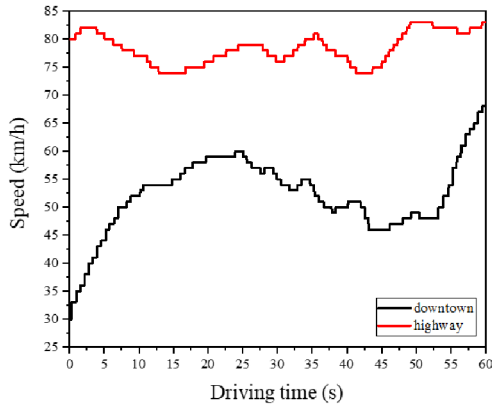


FIGURE 6. Real speed (wheel speed) of vehicle based on road types.

The variation in vehicle speed downtown varied significantly from around 30 to 68 km/h, but the speed varied only from 74 to 83 km/h on the highway. Generally, the variation in speed is broad in the downtown area, owing to traffic congestion. In contrast, the vehicle speed did not significantly vary on highways.

For the downtown area, the standard deviation of the speed was small, within 1.201, when the speed measurement unit was 30 m, as shown in Table 5. Conversely, the standard deviation was 3.808 and 12.153 when the speed measurement units were 100 m and 1 km, respectively, which are significantly higher than that for 30 m. The average speed for the sections of 100 m and 1 km could not be used to represent the speeds of these sections.

TABLE 5. Standard deviations of speed according to road type and measurement unit.

Road type	Unit of measure	Average time (s)	Average speed (km/h)	Standard deviation
Downtown	30 m	2.405	49.066	1.201
	100 m	8.283	47.924	3.808
	1 km	82.733	45.749	12.153
Highway	30 m	1.442	76.914	0.497
	100 m	4.717	78.509	1.204
	1 km	47.662	77.373	2.288

For the highway, the standard deviation of the speed was as small as 0.497 and 1.204 when measured in units of 30 and 100 m, respectively. However, a short driving period of  $\sim 1$  s was applied for units of 30 m. Additionally, if the time period was small, the bound of the speed would increase if the speed were measured. Moreover, the standard deviation of the speed was 2.288 for a unit of measurement of 1 km, which is slightly larger than that for 30 and 100 m.

2) RESULT OF DOWNTOWN ENVIRONMENT

The reliability of the measurement speed in the downtown environment was compared with the real speed. The driving speeds downtown and along the highway were measured in units of 30 and 100 m, which provided small standard

deviations, as mentioned. The speed of the vehicle was measured at intervals of 30 and 100 m, as depicted in Fig. 7, where each reference point is marked as A, B, . . . , J (Fig. 7(a)) for 30 m and A', B', . . . , D' (Fig. 7(b)) for 100 m intervals.



FIGURE 7. Reference points for measurements downtown at (a) 30 m and (b) 100 m units.

The distance between the reference points depicted in Fig. 7 was measured using the distance measurement function provided by satellite maps, such as Google Earth [30] and Kakao Map [31] the results are listed in Table 6. The distance was evaluated by setting the error range ( $\delta$ ) to 1, 2, or 3 m.

TABLE 6. Distance measurement results for downtown.

Measurement unit	Section (Start–End)	Distance (m)					
		Error ( $\delta = 1$ )		Error ( $\delta = 2$ )		Error ( $\delta = 3$ )	
		$d_{min}$	$d_{max}$	$d_{min}$	$d_{max}$	$d_{min}$	$d_{max}$
30 m (Fig. 7(a))	A–B	35	37	34	38	33	39
	B–C	28	30	27	31	26	32
	C–D	30	32	29	33	28	34
	D–E	29	31	28	32	27	33
	E–F	29	31	28	32	27	33
	F–G	30	32	29	33	28	34
	G–H	30	32	29	33	28	34
	H–I	31	33	30	34	29	35
	I–J	29	31	28	32	27	33
100 m (Fig. 7(b))	A'–B'	99	101	98	102	97	103
	B'–C'	99	101	98	102	97	103
	C'–D'	100	102	99	103	98	104

Table 7 lists the time measurements for the course portrayed in Fig. 7. The frame number at which the vehicle passed each reference point was determined, and the driving time of the car was calculated using the dashcam video.

The comparison between the real speed of the vehicle and that measured using a dashboard video for approximately 660 frames (i.e., 21.7 s) is presented in Fig. 8. The distance error range was set to 1 m for a measurement interval of 30 and 3 m for 100 m. Moreover, the distance error of the satellite was confirmed to be in the centimeter range for a measurement unit of 30 m [32], whereas the distance error on

TABLE 7. Time measurement results for downtown.

Measurement unit	Section (Start–End)	Start point (frame number)	End point (frame number)	Time (s)	
		$F_i$	$F_j$	$t_{min}$	$t_{max}$
30 m (Fig. 7(a))	A–B	0	130	4.3	4.37
	B–C	130	208	2.57	2.63
	C–D	208	282	2.43	2.5
	D–E	282	348	2.16	2.23
	E–F	348	410	2.03	2.1
	F–G	410	475	2.13	2.2
	G–H	475	537	2.03	2.1
	H–I	537	601	2.1	2.17
	I–J	601	659	1.9	1.97
100 m (Fig. 7(b))	A'–B'	0	290	9.63	9.7
	B'–C'	290	500	6.97	7.03
	C'–D'	500	697	6.53	6.6

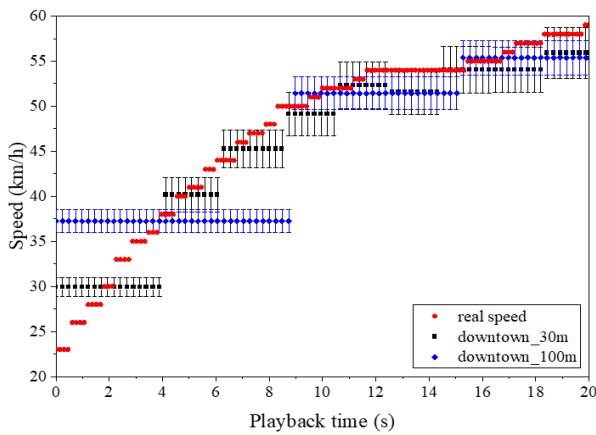


FIGURE 8. Comparison of real and measured speeds from the original video (type 1) in downtown.

the satellite map was in the meter range on the satellite map for a distance measurement unit of 100 m. Notably, a long distance interval may cause a curved road to occur, which increases satellite error. The empirical results indicated that the distance error was 1 m for every 30 m. Hence, the error range at 3 m units was 100 m.

In Fig. 8, the upper and lower bars of the measured speed (*downtown\_30m*, *downtown\_100m*) indicate the range of the maximum ( $s_{max}$ ) and minimum ( $s_{min}$ ) speeds. Additionally, there was a slight difference between the real and measured speeds at around 10 s from 0 to 282 frames, because the actual speed varied rapidly. However, the speed increased consistently, and the overall speed was slightly faster within the range of the measured speed, because the speedometer of the vehicle should not be less than the real speed on a flat road, as per Article 54 Paragraph 1 and Article 110 Paragraph 2 of MANAGEMENT ACT under the Korean law [38]. Furthermore, the speedometer should be designed to display the speed of within +10 % plus 6 km/h of the real speed. The average speed measured from the dashcam video was similar to the overall real speed, although the real-time response in areas was challenging at low speeds because the speed varied significantly on the downtown road.

### 3) RESULT OF HIGHWAY ENVIRONMENT

Next, the actual speed was compared to verify the reliability of the measurement speed in the highway environment. Similar to the method implemented downtown, the vehicle speed on the highway was measured based on the reference points depicted in Fig. 9, where each was set as A, B, . . . , J (Fig. 9(a)) at intervals of 30 m and as A', B', . . . , D' (Fig. 9(b)) at intervals of 100 m. Additionally, the distance and time measured by dividing the measurement unit into 30 and 100 m are listed in Tables 8 and 9, respectively.

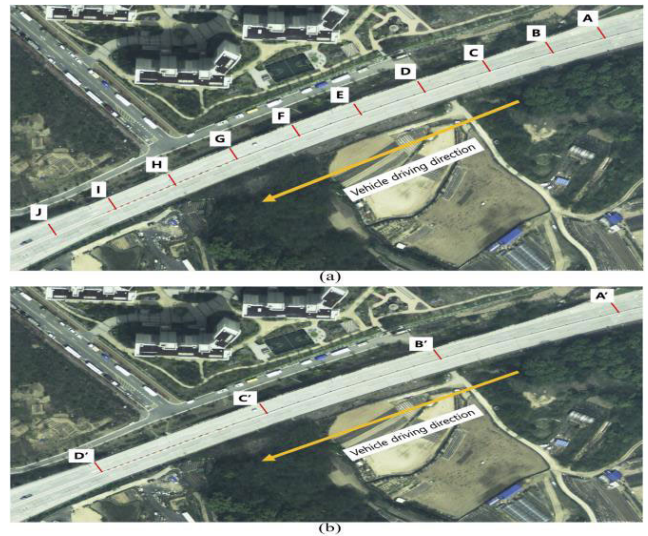


FIGURE 9. Reference points for measurement on highway: (a) 30 m unit; (b) 100 m unit.

TABLE 8. Distance measurement results on highway.

Measurement unit	Section (Start–End)	Distance (m)					
		Error ( $\delta = 1$ )		Error ( $\delta = 2$ )		Error ( $\delta = 3$ )	
		$d_{min}$	$d_{max}$	$d_{min}$	$d_{max}$	$d_{min}$	$d_{max}$
30 m (Fig. 9(a))	A–B	29	31	28	32	27	33
	B–C	36	38	35	39	34	40
	C–D	37	39	36	40	35	41
	D–E	37	39	36	40	35	41
	E–F	37	39	36	40	35	41
	F–G	37	39	36	40	35	41
	G–H	37	39	36	40	35	41
	H–I	37	39	36	40	35	41
	I–J	37	39	36	40	35	41
100 m (Fig. 9(b))	A'–B'	102	104	101	105	100	106
	B'–C'	105	107	104	108	103	109
	C'–D'	102	104	101	105	100	106

The real speed of the vehicle was compared to the speed estimated from the dashcam video for 15 s, approximately 450 frames, as illustrated in Fig. 10. Similar to that for downtown, the distance error of the satellite map on the highway was 1 m for 30 m and 3 m for 100 m. On the highway, the real speed of the vehicle did not vary considerably, and the real speed tended to be slightly higher than the measured speed but, overall, the real speed was within the range of the maximum ( $s_{max}$ ) and minimum ( $s_{min}$ ) speeds.



TABLE 9. Time measurement results on highway.

Measurement unit	Section (Start-End)	Start point	End point	Time (s)	
		(frame number) $F_i$	(frame number) $F_j$	$t_{min}$	$t_{max}$
30 m (Fig. 9(a))	A-B	12	52	1.3	1.37
	B-C	52	103	1.67	1.73
	C-D	103	156	1.73	1.8
	D-E	156	209	1.73	1.8
	E-F	209	264	1.8	1.87
	F-G	264	320	1.83	1.9
	G-H	320	375	1.8	1.87
	H-I	375	432	1.87	1.93
	I-J	432	489	1.87	1.93
100 m (Fig. 9(b))	A'-B'	0	141	4.67	4.73
	B'-C'	141	291	4.97	5.03
	C'-D'	291	445	5.1	5.17

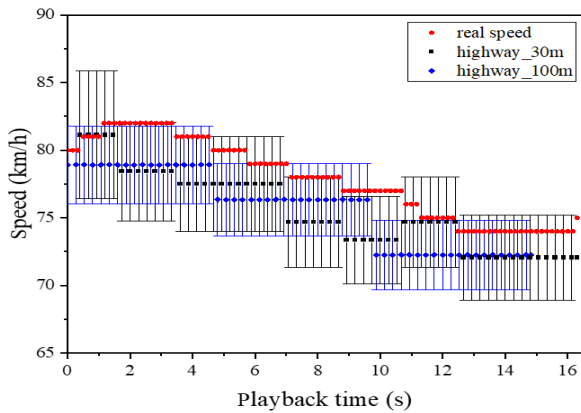


FIGURE 10. Comparison of real and measured speeds from the original video (type 1) on highway.

Nevertheless, the real speed of the vehicle was slightly higher, owing to the abovementioned Korean law. Considering that the range of the minimum and maximum speeds was within 5 km/h of the average speed, the measured speed was similar to the real speed.

C. VALIDATION OF MEASURED SPEED IN RETAKE AND RE-ENCODED VIDEOS

If a crime occurs, the investigator can retake the original videos recorded from dashcams if extraction is difficult. Additionally, the people involved in the accident may submit re-encoded videos via e-mail or smartphone messenger for maintaining privacy and convenience. Under these circumstances, it is difficult to verify that the submitted dashcam video has been manipulated. Hence, the speed measured based on the same manner was verified in the retake (type 2) and re-encoded (type 3) videos collected in these cases.

The speed measured by the proposed method was validated based on the variation in fps and playback speed. Thus, the experiments were conducted using the original videos of the downtown road (Fig. 7) and highway (Fig. 9), as listed in Table 4.

1) RESULT OF MEASURED SPEED FOR ROAD TYPE

We experimented with the effect of changing the fps and playback speed according to the road environment. The downtown and highway scenarios, files #1 (downtown\_original) and #2 (highway\_original), were manipulated with playback speeds of  $0.5 \times$  and fps of 24 for files #3 (downtown\_0.5x\_24fps) and #4 (highway\_0.5x\_24fps).

To reduce the speed deviation, the speed was measured by setting the 30 m interval and distance error to one, and the reference point was set as Fig. 7(a) for downtown and Fig. 9(a) for highway.

Figure 11(a) shows the speed measured in the downtown environment. The speed measured with file #1 (downtown\_original) is the baseline, and the speed measurement results were compared with the proposed method and VSEM [12]. Fig. 11(b) shows the speed measured by the proposed method and VSEM [12] for file #4 (highway\_0.5x\_24fps) with the playback speed and fps changed, with file #2 (highway\_original) as a baseline in the highway environment.

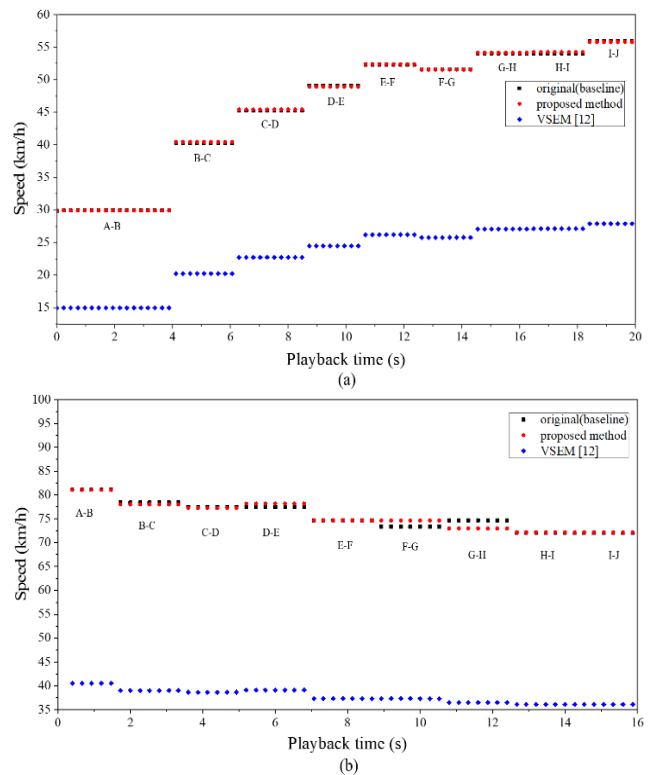


FIGURE 11. Average speed of manipulated video (file #3, file #4) according to road environment: (a) file #3 in downtown; (b) file #4 on highway.

As shown in Fig. 11(a), when file #3 (downtown\_0.5x\_24fps) was measured using the VSEM [12], the difference was about 15 km/h in section A-B and more than 20 km/h in the section after B-C. In contrast, the speed measured by the proposed method was found to be within 0.2 km/h of the baseline, with no significant differences in all sections.

In Fig. 11(b), the speed of the baseline was near 80 km/h; hence, it can be seen that the difference from the speed measured by the VSEM [12] was larger. The speed in file #4 (highway\_0.5×\_24fps) measured by the proposed method differed from the baseline within 1 km/h. However, when measured by the VSEM [12], there was a difference of about 40 km/h.

When measuring files #3 (downtown\_0.5×\_24fps) and #4 (highway\_0.5×\_24fps), which are videos edited at 0.5× and 24 fps, it was confirmed that the playback speed is affected by the speed measurement and is measured as half the speed of the baseline. However, the speed measured by the proposed method was not affected by the playback speed and was similar to the baseline within 0.2 km/h. In both files #3 (downtown\_0.5×\_24fps) and #4 (highway\_0.5×\_24fps), *fds* was calculated as 48 in the detection phase, and the *dps* was two because the *fps* was 24. Hence, it was calibrated according to (4) in Section III. Thus, it was confirmed that the speed can be measured robustly, even when the video is manipulated by changing the playback speed.

## 2) PLAYBACK SPEED MANIPULATION

We experimented with the effect of changes in playback speed on the speed measurement. First, because it is a speed measurement according to the change in the playback speed, file #2 (highway\_original) of Table 4 in the highway environment having less speed deviation was edited to be 0.5×, 0.7×, and 1.5×, respectively, with 30 fps, the same as file #2.

Figure 12 shows the results of the speed measured by the proposed and VSEM [12] methods for each file whose playback speed was changed. When the *fps* was the same, the speed measured by the proposed method was similar to the baseline in the situation where only the playback speed was edited. In file #5 (highway\_0.5×\_30fps), *fds* was calculated as 60; in file #6 (highway\_0.7×\_30fps), it was calculated to be 43; and in file #7 (highway\_1.5×\_30fps), it was calculated to be 20. The *dps* measurements were 2, 1.43, and 0.67, as calibrated for changes in playback speed.

When the speed of file #5 (highway\_0.5×\_30fps) was measured using the proposed method shown in Fig. 12(a), it was similar to the original at 0.05 km/h in most sections. It differed by 1.3 km/h in Sections A–B, F–G, and G–H. However, the range of *s<sub>min</sub>* and *s<sub>max</sub>* in the A–B, F–G, and G–H sections of the baseline were 76.3–85.8, 70.1–76.7, and 71.4–78 km/h, respectively. The ranges of *s<sub>min</sub>* and *s<sub>max</sub>* in the same sections measured by the proposed method were 76.4–83.7, 72–77.3, and 70.7–75.9 km/h, respectively. We see that the results of the speed measured by the baseline and the proposed method intersect. In contrast, the speed measured by the VSEM [12] was measured about 40 km/h lower than the baseline.

Figs. 12(b) and (c) are also observed similarly to Fig. 12(a). The proposed method did not differ significantly from the baseline, and there was a difference of about 2 km/h in some sections. However, this occurred while calculating the

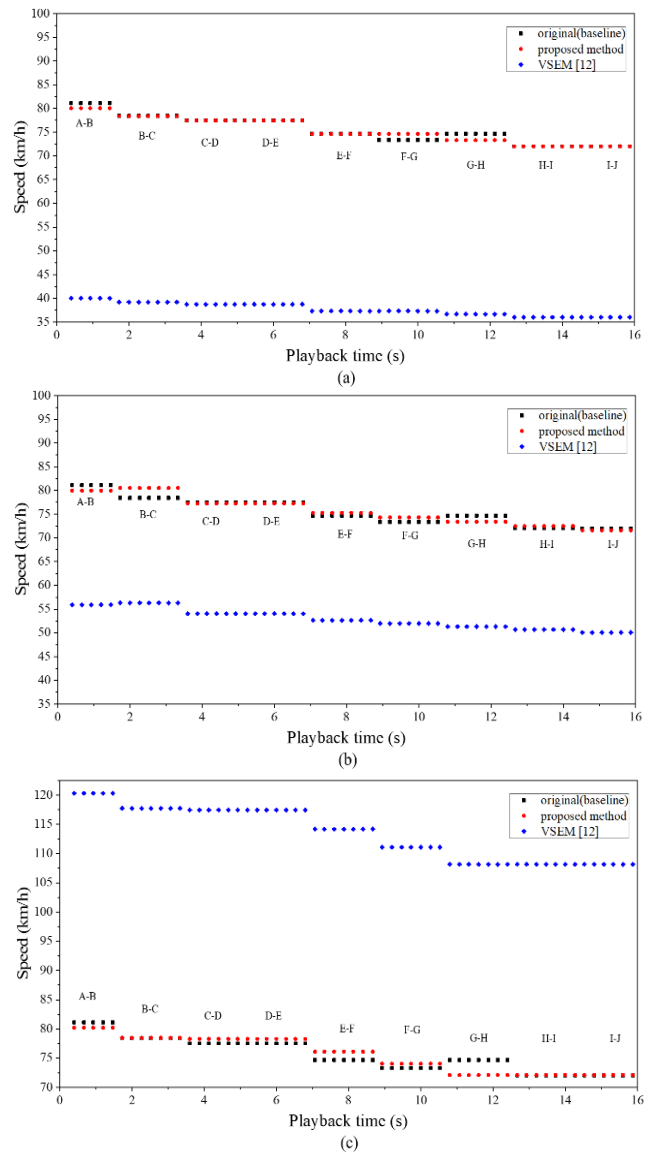


FIGURE 12. Average speed of type 2, 3 videos (file #5 ~ #7) with changed playback speed: (a) 0.5× (file #5); (b) 0.7× (file #6); (c) 1.5× (file #7).

average speed, and the *s<sub>min</sub>* and *s<sub>max</sub>* intersected within a similar range.

The speed by the VSEM [12] was measured as low at about 25 km/h in file #6 (highway\_0.7×\_30fps) and as high as 40 km/h in file #7 (highway\_1.5×\_30fps). The VSEM [12] can be greatly influenced by the playback speed of the video, such that the vehicle speed becomes slower or faster according to the ratio of the playback speed.

As such, it was confirmed that the playback speed significantly affects the measurement speed when it is intentionally edited. However, the proposed method shows that an accurate speed can be measured without being affected by the playback speed by calibrating it with the *dps*.

## 3) FPS MANIPULATION

We also experimented with the effect of *fps* changes on the measurement speed of the proposed and VSEM [12] methods.

TABLE 10. Average speed measurement results on various FPS.

File No		Sections (Start–End)								
		A–B	B–C	C–D	D–E	E–F	F–G	G–H	H–I	I–J
file #2 (highway_original)	$s_{min}$	76.39	74.77	74	74	71.36	70.11	71.36	68.90	68.90
	$s_{max}$	85.85	82.08	81	81	78	76.58	78	75.21	75.21
	gap	9.46	7.31	7	7	6.64	6.48	6.64	6.32	6.32
	$s_{avg}$	81.12	78.42	77.5	77.5	74.68	73.34	74.68	72.06	72.06
file #8 (highway_1x_10fps)	$s_{min}$	74.57	72	70.11	74	66.6	70.11	66.6	66.6	66.6
	$s_{max}$	93	85.5	82.59	87.75	78	82.59	78	78	78
	gap	18.43	13.50	12.48	13.75	11.40	12.48	11.40	11.40	11.40
	$s_{avg}$	83.79	78.75	76.35	80.88	72.3	76.35	72.3	72.3	72.3
file #9 (highway_1x_24fps)	$s_{min}$	75.93	74.06	74.34	74.34	69.5	72.65	69.5	68.02	68.02
	$s_{max}$	86.4	82.08	82.19	82.19	76.58	80.23	76.58	74.88	74.88
	gap	10.47	8.02	7.84	7.84	7.09	7.57	7.09	6.86	6.86
	$s_{avg}$	81.16	78.07	78.26	78.26	73.04	76.44	73.04	71.45	71.45
file #10 (highway_1x_60fps)	$s_{min}$	77.33	75.5	74.69	74.69	72.65	72	70.73	69.5	70.73
	$s_{max}$	84.76	81.27	80.23	80.23	78	77.28	75.89	74.55	75.89
	gap	7.43	5.77	5.54	5.54	5.35	5.28	5.17	5.05	5.17
	$s_{avg}$	81.05	78.38	77.46	77.46	75.33	74.64	73.31	72.02	73.31

TABLE 11. Comparison based on Pearson's correlation coefficient of original and manipulated videos.

	0.5x	0.7x	1.5x	0.5x and fps 24	fps 10	fps 24	fps 60
Original	0.99948	0.99908	0.99857	0.99947	0.99597	0.99831	0.99949

As before, file #2 (highway\_original) in the highway environment with low speed deviation was edited with files #8–10 at 10, 24, and 60 fps, respectively. The playback speed was the same as the original at 1×. The playback speed was 1× and the  $dps$  was confirmed to be one. Hence, the proposed and VSEM [12] method were measured equally.

The speed measurement results for file #2 (highway\_original) and various fps measurements of files #8–10 are shown in Table 10. The average speed measured in the four files were similarly observed at about 2 km/h; hence, the measurement speed was not significantly influenced by fps. However, we can see that the gap between  $s_{min}$  and  $s_{max}$ , which is the range of vehicle speed, varied greatly with fps.

We found that the gap between  $t_{max}$  and  $t_{min}$  increased as the fps decreased. The time interval between  $t_{max}$  and  $t_{min}$  was 0.2 s at fps measurements of 10, 0.09 s at fps 24, 0.07 s at fps 30, and 0.03 s at fps 60, because the larger fps corresponds to more video frames recorded per second. Therefore, a smaller fps can result in a larger measurement speed error, and a larger fps can reduce the measurement speed error. The results of the measured speed are presented in Table 10.

In the case of file #8 (highway\_1×\_10fps) with 10 fps,  $s_{min}$  differed from file #2 (highway\_original) by about 2.51 km/h on average and, in particular, it differed greatly at about 4 km/h in sections C–D, E–F, and G–H. The  $s_{max}$  had a difference of 3.39 km/h on average, but it was 6 km/h in sections A–B, D–E, and F–G, resulting in a significant difference in the vehicle's speed range, which can reduce the accuracy of the measured speed.

Files #9 (highway\_1×\_24fps) and #10 (highway\_1×\_60fps) with fps measurements of 24 and 60 did not show much difference from file #2 (highway\_original) in  $s_{min}$  and  $s_{max}$  of about 1 km/h. It can be seen that this does not affect the result of speed measurement in terms of accuracy unless it is a significantly low level of fps, such as 10 fps.

#### 4) STATISTICAL VERIFICATION OF PROPOSED METHOD

The correlation coefficient results are comparatively presented in Table 11. Additionally, the measurement results of type 2 (retake) and type 3 (re-encoded) videos were statistically validated for cases involving purposeful manipulation of the fps and playback speed to evade responsibility for an accident. Moreover, the speed measured by the proposed method at a total of 24 sections in the downtown and highway environments (Figs. 7 and 9) were statistically validated. For the 24 sections, the Pearson's correlation coefficient of the average speed in the original video and 0.5×, 0.7×, and 1.5× videos by types 2 and 3 were 0.99948, 0.99908, and 0.99857, respectively. Furthermore, comparing the original video with that at 0.5× at 24 fps with varying fps and playback speeds, the correlation coefficient was confirmed as 0.99947. If the fps was altered, the Pearson's correlation coefficient was 0.99597, 0.99831, and 0.99949 upon comparing the original with the 10-, 24- and 60-fps videos, respectively.

According to Akoglu [39], a Pearson's correlation coefficient of  $\pm 1$  indicates a strong agreement and zero suggests the strongest disagreement. In context, all the results of our experiments yielded values of almost one, indicating

that the speed measured from the dashcam video was valid for retake and re-encoded videos. However, the results for 10 fps appeared to be the lowest, because a large gap existed between  $s_{max}$  and  $s_{min}$ . Therefore, a deviation occurred while calculating the average speed, but 0.99597 is extremely close to one, and the result can therefore be deemed valid.

## V. CONCLUSION

In this study, we proposed a vehicle speed measurement method using dashcam videos, including retaken videos of an accident scene when the original video could not be directly extracted, or the submitted video (retake or re-encoded) could not be guaranteed to be unaltered. In particular, various manipulations are possible in retaken or re-encoded videos. However, the method proposed in this study accounts for deliberate manipulations of playback speed to ensure reliable measurements of vehicle speed.

First, the accuracy of the proposed method was measured and compared with the actual vehicle speed. The real speed of the vehicle was compared with that measured using dashcam videos based on the road environment (i.e., downtown or highway), indicating that the low vehicle speeds in the downtown area were not synchronized in real-time, owing to frequent changes in speed. However, the average speed of the low-speed sections was similar to the measured speed. Excluding those sections, experimental results revealed that there was no difference between the real and measured speeds because the variation in speed was not significant in other locations.

In this study, the speed measured in the retaken and re-encoded videos were determined to be reasonable compared with its original value. Even for the retaken and re-encoded videos, we compared the measured speeds in cases involving altered playback speed. The proposed method detected the average speed similar to the original video by calibrating it with the measured  $dps$ , and the range of the maximum and minimum speeds overlapped regardless of the variation in playback speed. The conventional method, on the other hand, showed that the differences between the measured and actual speeds changed with playback speed.

Moreover, the experimental results revealed that the average speed was predominantly within the range of the minimum and maximum speeds for various fps measures. Furthermore, a comparative analysis based on Pearson's correlation coefficient yielded results that were all close to one; hence, the measured speeds were similar for varying playback speeds and/or fps measures in the same section. This validates the proposed method for measuring speeds from the retake and re-encoded videos. In the downtown and highway road environments, the proposed method accurately measured vehicle speeds regardless of alteration of playback speeds in the original video.

Our verified method will play an important role in deriving reliable results from various evidential videos. In the future, we plan to expand the scalability of the proposed method to demonstrate its validity in diverse environments.

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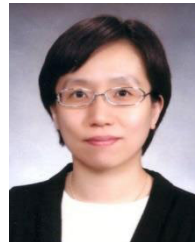
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