Anisotropic Magnetoresistive 센서를 이용한 차량 검지기의 성능분석

논 문
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Performance Analysis of an Anisotropic Magnetoresistive Sensor-Based Vehicle Detector

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Abstract - This paper proposes a vehicle detector with an anisotropic magnetoresistive (AMR) sensor and addresses experimental results to show the detector's performance. The detector consists of an AMR sensor and mechanical and electronic apparatuses. The AMR sensor, composed of four magnetoresistors, senses disturbance of the earth's magnetic field caused by a vehicle moving over the sensor and then produces an output indicative of the moving vehicle. This paper verifies performance of the detector on the basis of experimental results obtained from the field tests carried under the two traffic conditions on local highways in Korea. First, I show the vehicle counting performance on a low speed congested highway by comparing the vehicle counts measured by the detector with the exact counts. Second, both vehicle counts and average speeds calculated from the measured point-occupancy on another continuously free running highway are compared with the reference values obtained from a loop detector which has two independent loop coils, where I have used several performance indices including mean absolute percentage error (MAPE) to show the performance consistency between the two types of detectors.

Key Words : Vehicle detector, AMR sensor, Vehicle counting, MAPE

I. Introduction

Vehicle detector is the most fundamental element of the Transportation Management Systems (TMS) that is used to collect information from moving vehicles on the road, such as the traffic volume, the occupancy rate, and the speed. Among the prior state-of-the-art vehicle detectors the loop detector has been used on the largest area due to its low cost and relatively high performance [1-4]. Generally, the loop detector is considered to be superior to the other detectors in standard operation. But, the installation of the loop requires tearing up the road and the loop can be seriously damaged by the thermal expansion of the highway. Even a small shape-distortion of the loop can make the detecting performance deviate seriously from the normal state. An earth magnetic field (EMF) detector, based on magnetoresistive (MR) sensors [7-10], was suggested in [3] as an alternative to the loop detector. This detector senses disturbance of the EMF caused by a moving vehicle over the sensor and then produces an output indicating the moving vehicle. Vehicle detectors with MR sensors are small in size and hardly changed in shape, which makes the installation and the repair very easy. Nevertheless, caused by the local shifts of the EMF according to the tested field, unpredictable offset of the MR sensor occurs, and this has been the main reason for the EMF detectors not to be in a great use.

Recently, vehicle detectors based on an anisotropic magnetoresistive (AMR) sensor have been proposed and tested in the field [5], [6]. Reference [5] demonstrates the effectiveness of a vehicle detect algorithm using an AMR sensor. And, reference [6] shows the practicality of an AMR sensor-based detector, through the field experiments for both analyzing detector's characteristics and measuring vehicle volume in a congested traffic condition. This paper shows results of recent field test, subsequent of [6] and verifies performance of an AMR detector more substantially. Both hardware and software configurations of the detector used in this test are almost same as those of the detector of [6] besides some parts as described in the chapter III.

In this paper, I verify performance of an AMR sensor-based vehicle detector on the basis of experimental results obtained from the field tests carried under the two different traffic conditions on local highways in Korea. First, I show the vehicle counting performance in a low speed congested highway,

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Mishiryong, by comparing the vehicle counts measured by a detector with the exact counts. Second, I compare both measured vehicle counts and average speeds calculated from the measured point-occupancy on another continuously running highway, Boingilcheon, with the reference measurements obtained from a loop detector which has two independent loop coils, where several performance indices, such as equality coefficient (EC), root mean square (RMS), mean absolute percentage error (MAPE), and correlation coefficient (CORR), are used to compare the performances of the two types of detectors.

II. Characteristics of an AMR Sensor

A KMZ51, an AMR sensor used in the detector, consists of four magnetoresistors which are made of a nickel-iron (permalloy) thin film deposited on a silicon wafer and patterned as resistive strips [10]. All the resistors are packaged in a solid-state body as shown in Fig. 1(a). If the resistance of the permalloy changes by the MR effect, output voltage of the resistor bridge (+Vo -Vo) changes accordingly. Fig. 1(b) shows origin of the MR effect in a material. When no external magnetic field is present, the material has an internal magnetic field (H_{in}) parallel to the current flow caused by the Vcc. If an external magnetic field (H_{ext}) is applied, the resultant magnetization vector of the material will rotate by α to be a vector, H_{tot}, which makes the resistance (R) of the material change as a function of the rotation angle, α, as follows:

$$R = R_0 + \Delta R_0 \cos^2\alpha \tag{1}$$

Where R_0 and ΔR_0 are material parameters.

Fig. 2 shows the amplified outputs of two AMR sensors (KMZ51) while a ferromagnetic object (magnet) moves over the two sensors where one sensor is located with its sensitive axis horizontal to the moving direction of the magnet and the other one is located with its sensitive axis perpendicular to the moving direction. In Fig. 2(a), lower curve represents a sensor output while the magnet moves along the sensitive axis of the AMR sensor. As the magnet moves, the sensor output increases above an initial value, and then decreases to the same level as the initial value when the magnet is placed above the sensor, then decreases below the initial level. But, while the magnet moves perpendicularly to the sensitive axis of the sensor, the sensor output is quite different from the lower curve. Namely, as the upper curve in Fig. 2(a) shows, when the moving magnet is placed directly above the sensor, the sensor's output increases to be the maximum and then decreases to the initial level. Also, the upper curve, the case of the sensitive axis perpendicular to the moving magnet, increases and decreases quite sharply than the lower curve, the case of the sensitive axis being along the moving magnet. This sharpness can be a desirable effect on the discrimination of two closely and successively moving objects [6].

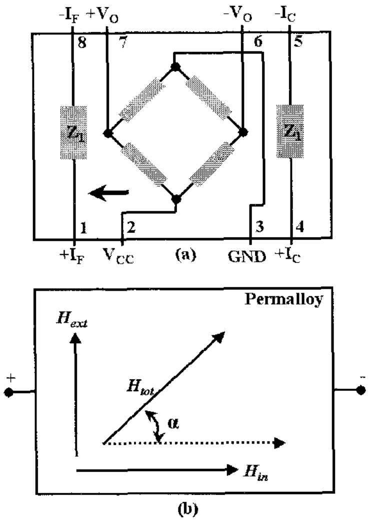

Fig. 1 (a) Equivalent circuit of a KMZ51 (The arrow indicates the direction of the sensitive axis.) and (b) MR effect (Hin: internal magnetic field, Hext: external magnetic field, Htot: resultant magnetic field).

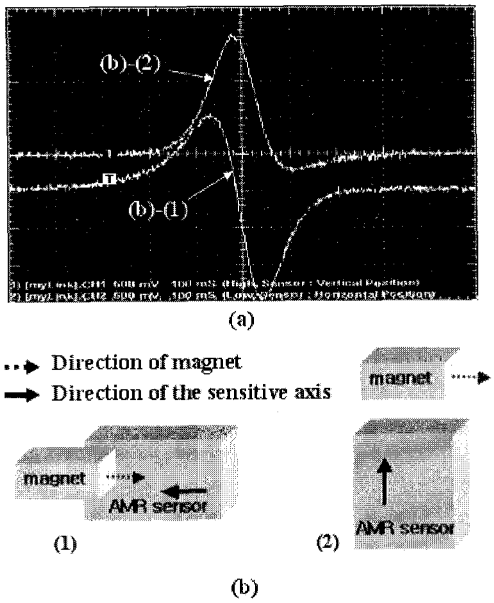

Fig. 2 (a) Amplified sensor outputs (x: 100 ms/div, y: 500 mV/div) and (b) arrangement of a magnet and an AMR sensor for experiments.

When AMR sensors are exposed to a disturbing magnetic field, the output voltage of the sensor would hardly return to its initial level accurately and has a little offset from the level. Fig. 3(a) shows this offset of the output that is not reduced and somewhat magnified. This offset could be a major obstacle to the stable operation of AMR sensors. To solve this problem, flipping current pulses should be applied into a flipping coil strip of the AMR sensor (+IF −IF, see Fig. 1(a)), periodically from the beginning of the detecting operation so that a strong magnetic field is generated and periodically realigns the magnetic domains into the initial state. According to the datasheet [10] the minimum flipping current is recommended to be 1000mA with minimum pulse width of 3μs, so the sensor board of this paper is designed complying with this current rating. Fig. 3(b) shows no offsets removed by the flipping current. Though the voltage flashes caused by the current pulses are shown in this figure, they have no influence on the vehicle detecting procedure.

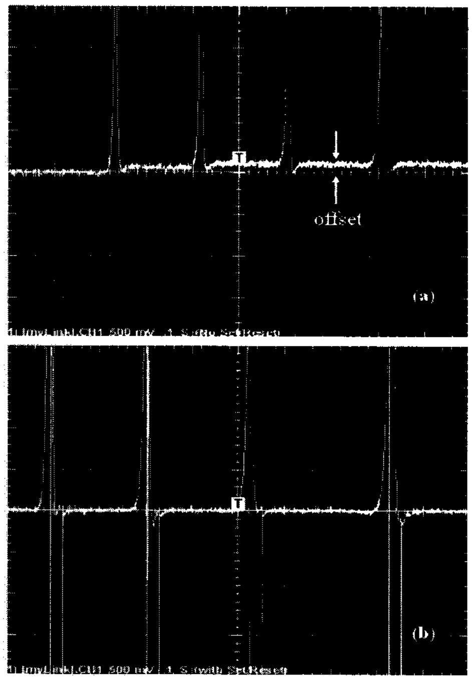

Fig. 3 Amplified outputs of a KMZ51 (a) without flipping current and (b) with flipping currents (x: 1 s/div, y: 500 mV/div)

III. Field Experiments

Performance of a vehicle detector is verified on the basis of experimental results obtained from the field tests carried under the two different traffic conditions on local highways in Korea. First, vehicle counting performance in a low speed congested highway, Mishiryong, is shown, then, performance for both vehicle counts and averaged speeds on another continuously running highway, Boingilcheon, are shown and compared with the reference values obtained from a loop detector having two independent loop coils.

A. Case I: Low Speed Congested Highway

The developed detector has been tested on a local highway in Mishiryong in Korea. Tested field was set up, firstly to measure the detector's output voltage waveforms for different moving vehicles. In multi-lane highway, an AMR sensor in a vehicle detector, buried in a lane, could be affected with the ferromagnetic vehicles driving on other lanes and this gives incorrect information, so the sensor should be arranged carefully to reduce this interference [6]. Fig. 4 shows the output curves of the vehicle detector according to the different types of vehicles traveling over the detector on the highway. Fig. 4 reveals very detailed magnetic signature of the passing vehicle, and therefore, the outputs of the detector could be used to extract various traffic information. And the figure shows that every driving vehicles produce voltage fluctuations over 0.3V so, this voltage can be selected as the voltage threshold level which is used to determine vehicle presence over the sensor.

Fig. 5 shows experimental results obtained on the highway during a highly congested traffic condition, about below 10 km/h averagely. Three curves in the Fig. 5 show the number of the passing vehicles according to the time-elapse on a lane of the highway. A ratio of the measured number of vehicles to the exact number of vehicles (set to 100), measured-count/exact-count, is noted for each curve in the legend. Generally, vehicle detectors have difficulty in discriminating between vehicles that move bumper-to-bumper in congested traffic and may count a larger number of vehicles than the exact number [4]. But, the curves show that counting error is 0.3% on average, and that proposed vehicle detector with an AMR sensor has good count performance for low speed congested traffic.

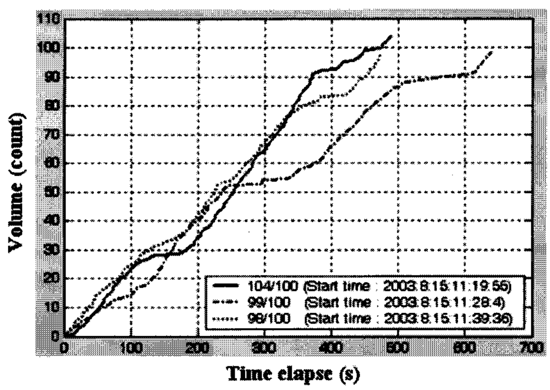

Fig. 5 Number of vehicles driving on a low speed congested highway.

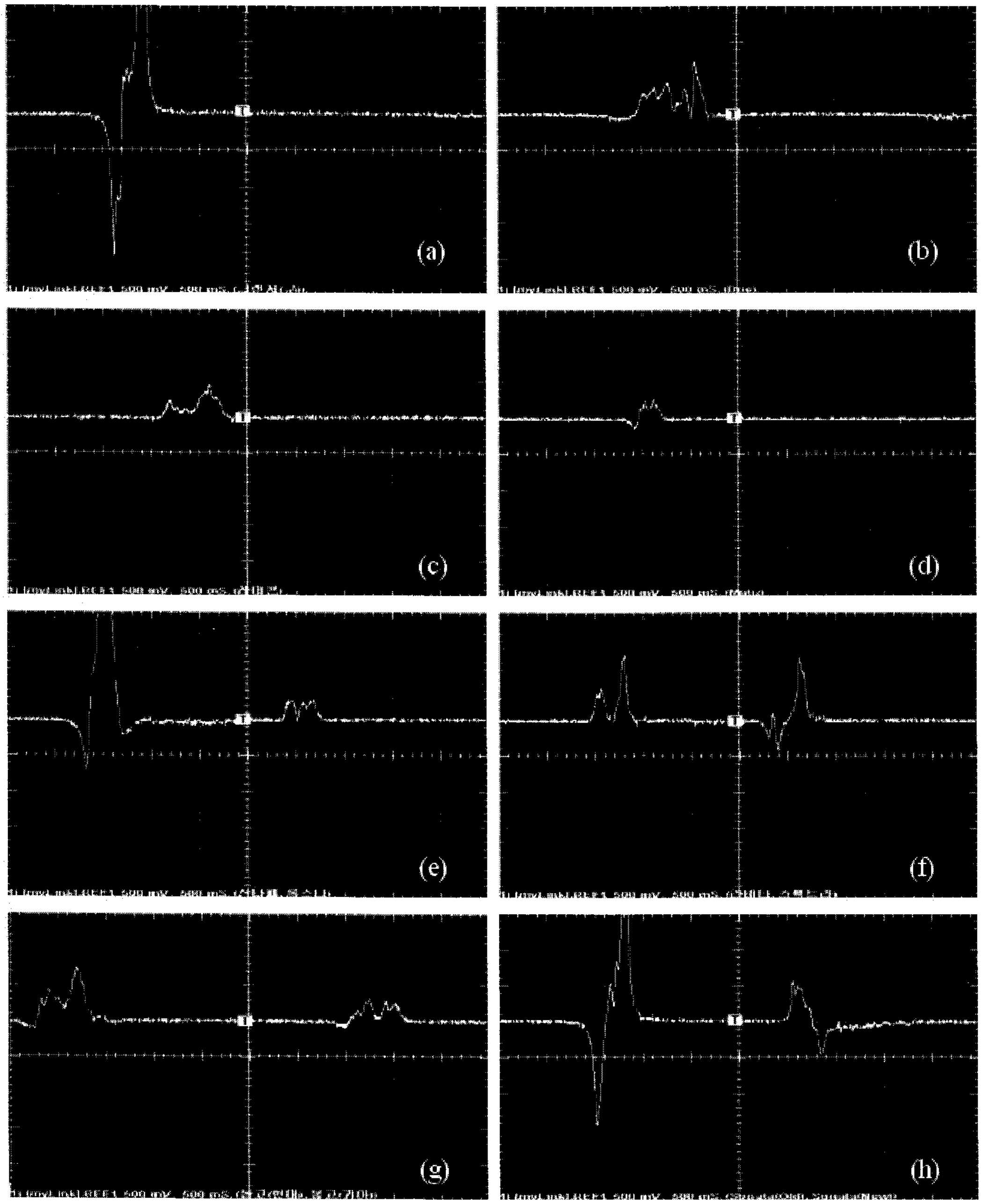

Fig. 4 Output curves of an AMR detector according to various vehicles traveling over the detector on a highway (a) a large size sedan, (b) a bus, (c) a special truck (remicon), (d) a light-weight passenger car, (e) two RVs (van and jeep), (f) a small size passenger car (hatchback) and a small size sedan, (g) two 1-ton trucks, and (h) two medium size sedans (old and new version) (x: 500 ms/div, y: 500 mV/div).

B. Case II : Continuously Free Running Highway

Both hardware and software configurations of an AMR detector used in this test are almost same as those of the detector used in [6] besides some parts - batteries, Real Time Clock (RTC), a RF transceiver, and 4MBits flash memory to save vehicle counts, occupying time, and the passing date of each vehicle that passes over the detector. The occupying time is saved to calculate average point-speed of each passing vehicle. Collected vehicle data can be transferred to a PC through a serial port after experiment has finished, or wirelessly transferred to a local data-logger via a RF transceiver in real-time. And the mechanical apparatus of the detector is modified so that the detector can be used portably and attached (not buried) on the road. The setup is straightforward, requiring only about 1 minute. Fig. 6(a) shows a photograph of the detectors attached on the tested local highway in Korea, Boingilcheon, and Fig. 6(b) shows configuration of the detectors. The dimension of a detector is 8cm × 12 cm × 1.5cm (W×L×H) and it is stiffly attached in the middle of the lane with an adhesive tape.

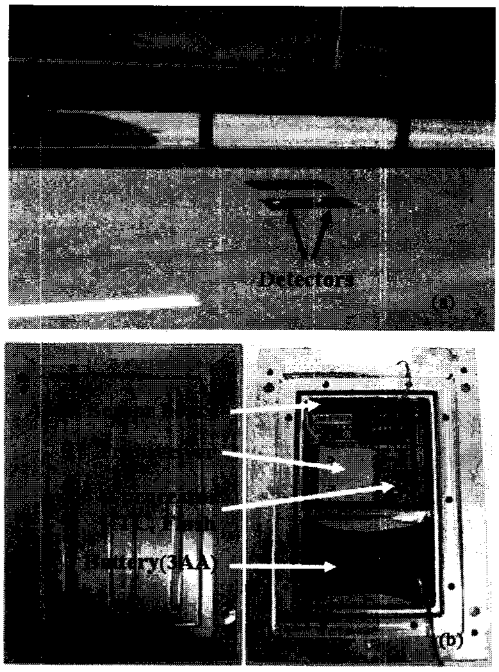

Fig. 6 (a) Two attached detectors on a local highway, Boingilcheon and (b) case of a detector and its internal configuration.

Counting of a vehicle is simply realized by a window comparator where if the output voltage of a detector goes out of the window's upper (or lower) reference values a passing vehicle is detected. At this point, the detector starts a timer (t0) and waits for the vehicle having passed out of its detect range. If the output voltage of the detector recovers from an excited level and then it remains continuously within the window for a predefined time (t), set to 0.3 s, the vehicle is decided to be out of the detect range, when a counting process has finished, and the detector catches the timer output (t1) again and calculates the occupying time (toc) as t1 - t0 - t. Count, occupying time, and passing date for each vehicle are saved in the flash memory over 24-hours and transferred to a computer after the experiment has finished.

The 24-hour data are divided into 10-minute intervals that are used to calculate average speed and performance indices such as EC, RMS, MAPE, and CORR. These indices are selected to estimate under various respects the degree of performance consistency of the AMR detector with a reference inductive loop detector. The indices are calculated as (2) where $f_{arm,i}$ and $f_{loop,i}$ mean measurements in the i-th 10-minute interval for AMR and loop detector. These measurements are to be replaced with a total number of counts for volume performance or with a average speed for speed performance. The total number of count is directly obtained from the total number of measurements, but the average speed has a difficulty in calculation. Because the detect range of an AMR detector is not clearly definable, the traveling distance of a vehicle during an occupancy time over the detector could not be determined exactly, though exact length of the vehicle is given. Thus, I define a terminology, effective vehicle length (l_{eff}), by adding the detect range to a vehicle length. l_{eff} is not a deterministic value and selected statistically, that is, after an initial value for l_{eff} is selected, each performance index for the average speed is calculated repeatedly with the l_{eff} while l_{eff} is changing around its initial value. Fig. 7 shows findings for this process with the initial l_{eff} of 4 m, from witch the best l_{eff} value is chosen reasonably to 4.3m because RMS and MAPE are smallest, and EC is largest at this value. After a value for l_{eff} has chosen, an average speed for each detector can be calculated by (3) for a 10-minute interval. For ARM detector, a vehicle speed is calculated first by dividing l_{eff} by an occupying time, toc, secondly, this procedure applies to all occupying times in a 10-minute interval to calculate all vehicle speeds, and lastly, all the speeds are added and divided by the total number of measurements in a 10-minute interval. For loop detector, all speed measurements in a 10-minute interval of loop data are added and then divided by the total number of measurements in that interval. Table I describes the symbols used in (2) and (3).

Fig. 8shows volume consistency between a tested AMR detector and a loop detector. For count accuracy, this result shows that EC, RMS, MAPE, and CORR of 10-minute intervals between the two detectors are about 0.99, 1.09 counts, 1.21 %, and 1.00. And, total counts of 24-hour test for each detector amount to 8809 and 8844, respectively. Fig. 9 shows average speed consistency between the AMR and loop detectors. EC, RMS, MAPE, and CORR of 10-minute intervals between the two detectors are calculated by using l_{eff} value of 4.3 m and they are found to be about 0.97, 3.52 km/h, 3.50 %, and 0.67, respectively. In summary, the test for volume indicates the AMR detector agrees excellently with the reference loop detector. And, for average speed, performance is found a little worse by about 2 % in RMS and MAPE than the result of the volume test, which is natural because the speed measurements of the loop detector are obtained from 2 loop coils with known distance.

$$EC \; : \; 1 - \frac{\sqrt{\sum_{i=1}^{n}(f_{amr,i} - f_{loop,i})^2}}{\sqrt{\sum_{i=1}^{n} f_{amr,i}^{\;2}} + \sqrt{\sum_{i=1}^{n} f_{loop,i}^{\;2}}}$$

$$RMS \; : \; \sqrt{\sum_{i=1}^{n}(f_{amr,i} - f_{loop,i})^2 / n} \qquad (2)$$

$$MAPE \; : \; \frac{100}{n}\sum_{i=1}^{n}\frac{|f_{loop,i} - f_{arm,i}|}{f_{loop,i}}$$

$$CORR \; : \; \frac{\sum_{i=1}^{n}(f_{amr,i} - \overline{f_{amr}})(f_{loop,i} - \overline{f_{loop}})}{\sqrt{\sum_{i=1}^{n}\left|f_{amr,i} - \overline{f_{amr}}\right|^2}\sqrt{\sum_{i=1}^{n}\left|f_{loop,i} - \overline{f_{loop}}\right|^2}}$$

$$\overline{s_{amr,i}} = \frac{1}{n_{amr,i}}\sum_{k=1}^{n_{amr,i}}\frac{3.6 l_{eff}}{t_{oc,i,k}} \;,\quad \overline{s_{loop,i}} = \frac{1}{n_{loop,i}}\sum_{k=1}^{n_{loop,i}} s_{loop,i,k} \qquad (3)$$

Table I Symbols for Performance Indices.

Symbol	Description	Unit
n	Number of 10-minute intervals in 24-hour data (=144)	-
$n_{arm,i}$, $n_{loop,i}$	Number of measurements in the i-th interval for AMR and loop detectors	-
$f_{arm,i}$, $f_{loop,i}$	Measurement (average speed or count) in the i-th interval for AMR and loop detectors	km/h or count
$\overline{f_{arm}}$, $\overline{f_{loop}}$	Average value for $f_{arm,i}$, $f_{loop,i}$	km/h or count
$\overline{s_{arm,i}}$, $\overline{s_{loop,i}}$	Average speed of the i-th interval for AMR and loop detectors	km/h
$s_{loop,i,k}$	k-th speed measurement in the i-th interval for loop detector	km/h
$t_{oc,i,k}$	k-th occupancy measurement in the i-th interval	s
l_{eff}	Effective vehicle length	m

V. Conclusion

This paper proposes a vehicle detector with an AMR sensor and addresses its performance on the basis of experimental results. Performance of a vehicle detector is verified on the basis of experimental results obtained from the field tests carried under the two different traffic conditions on local highways in Korea. The experimental results for the congested highway show that the vehicle detector with an AMR sensor has counting error of 0.3% on average. In the meantime, the experimental results for the continuously running highway conclude that, as for volume, EC, RMS, MAPE, and CORR of 10-minute intervals between an AMR detector and loop detector are

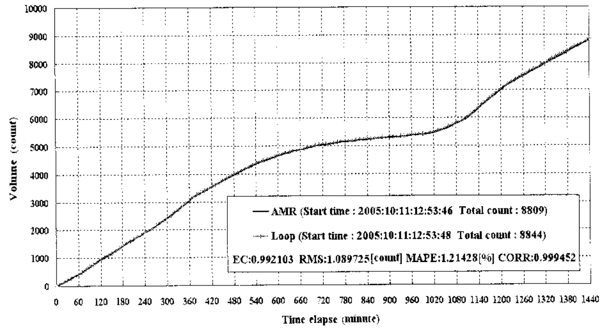

Fig. 8 Comparison of volumes between AMR and loop detectors using 10-minute intervals of 24-hour data.

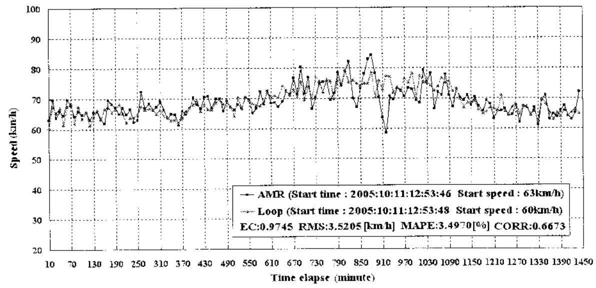

Fig. 9 Comparison of average speeds between AMR and loop detectors using 10-minute intervals of 24-hour data.

0.99, 1.09 counts, 1.21 %,and 1.00, and as for average speed, the indices of 10-minute intervals between the two detectors are 0.97, 3.52 km/h, 3.50 %, and 0.67. In summary, an AMR sensor-based detector has excellent performance for vehicle counting, but the average speed performance in the free running highway is a little worse by about 2 % than the volume performance in EC and MAPE. Future research will be focused on improving the average speed performance by using two AMR detectors and on wirelessly data transferring.

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