Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography
Vol. 39, No. 5, 253-263, 2021
https://doi.org/10.7848/ksgpc.2021.39.5.253

ISSN 1598-4850(Print)
ISSN 2288-260X(Online)
Original article

# Development of a Multiple Linear Regression Model to Analyze Traffic Volume Error Factors in Radar Detectors

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**Abstract**

Traffic data collected using advanced equipment are highly valuable for traffic planning and efficient road operation. However, there is a problem regarding the reliability of the analysis results due to equipment defects, errors in the data aggregation process, and missing data. Unlike other detectors installed for each vehicle lane, radar detectors can yield different error types because they detect all traffic volume in multilane two-way roads via a single installation external to the roadway. For the traffic data of a radar detector to be representative of reliable data, the error factors of the radar detector must be analyzed. This study presents a field survey of variables that may cause errors in traffic volume collection by targeting the points where radar detectors are installed. Video traffic data are used to determine the errors in traffic measured by a radar detector. This study establishes three types of radar detector traffic errors, i.e., artificial, mechanical, and complex errors. Among these types, it is difficult to determine the cause of the errors due to several complex factors. To solve this problem, this study developed a radar detector traffic volume error analysis model using a multiple linear regression model. The results indicate that the characteristics of the detector, road facilities, geometry, and other traffic environment factors affect errors in traffic volume detection.

Keywords : Multiple Linear Regression Model, Radar Detector, Cooperative Intelligent Transport Systems, Factor Analysis, Traffic Volume

## 1. Introduction

The aim of C-ITS (Cooperative Intelligent Transport Systems) is to create a fast and safe transportation system in line with the technological development of the information age. The advanced transportation equipment introduced by the development of C-ITS has made it possible to collect and accumulate a large amount of traffic information data. Currently, various advanced systems are in operation to collect traffic data. Recently, the technology for these collection processes has evolved into loop, radar, and imaging methods. Among them, radar detection is a leading technology in the vehicle detection market compared with other detectors based on advantages such as maintenance-saving costs, easy installation, few interference factors in the aggregation process, and the accuracy of collected traffic data(Ju, 2008). In addition, radar detectors present advantages such as fewer interference factors related to weather conditions and effecting multilane two-way road detection using one radar detector only(Fig. 1). However, it is difficult for radar detectors to determine the causes of missing or erroneous traffic volume. This is because the type of error in radar detectors can be caused not only by problems with the detector equipment but also by other elements such

Received 2021. 08. 23, Revised 2021. 09. 30 , Accepted 2021. 10. 07
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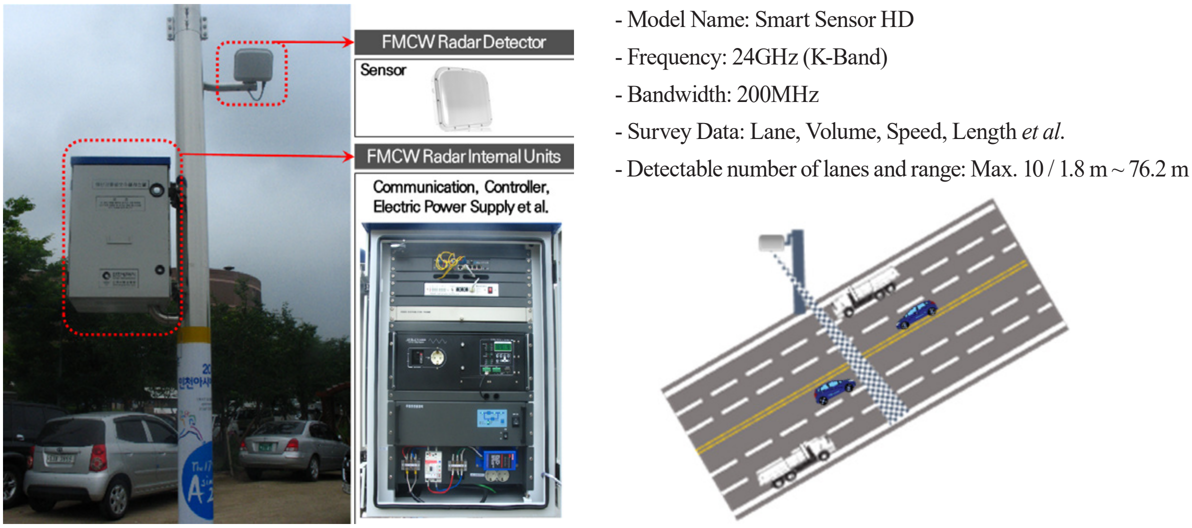



**Fig. 1. Specifications of the Radar Detector**

as traffic environment factors, road geometry, and driving behavior. To solve these problems, radar detector operators have primarily applied methods such as simple detector system adjustment and detector relocation based on basic engineering decision-making and experience. Nonetheless, it remains difficult to expect high accuracy in radar detector traffic data using this process. Accordingly, to be considered reliable, the accuracy of radar detector traffic data must be improved by analyzing the error factors.

## 2. Literature review

Despite the advanced equipment used for the realization of perfect C-ITS, vehicle detectors can include errors for many reasons. The accuracy of traffic volume data collected by a detector in such a system serves as the basis not only for gaining reliable traffic information but also for ensuring driver safety on roads. Its reliability must thus be guaranteed, which can be achieved through performance improvements and the appropriate evaluation of the detector equipment. This study reviewed existing studies related to performance evaluation according to detector types and by analyzing detector error factors.

Generally, existing studies indicate that the performance of nonburied detector types, such as radar detectors, is relatively low(Ju, 2008; Ryu *et al*., 1998; Ko, 2015; FHWA, 2006). However, compared with buried-type detectors, such as induction loop and magnetic detectors, nonburied detectors have the advantage of being able to detect traffic volume on multilane two-way roads. Nonburied detectors are, however, less accurate in relation to aggregated traffic volume, and this is due to factors such as detector installation height and radial angle, vehicle type and speed, radio transmission, and reception problems. The accuracy of traffic volume detection by radar detectors was higher among nonburied detectors, e.g., magnetic, laser, infrared, and image detectors(Minge *et al*., 2010). Contrastingly, studies conducting performance tests on nonburied(loop, radar, image, and coil sensor) detectors found that image detectors have the highest accuracy at 98% or more and radar detectors have the lowest accuracy at 74%(Ko *et al*., 2015). In addition, selected studies have demonstrated that the performance of radar detectors can be improved by adjusting the vehicle's driving speed and gap spacing between cars, the ratio of heavy vehicles, the location of the detector installation, and the height of the detector(Ko *et al*., 2015; Jang *et al*., 2005; Choi, 2010; Korea Institute of Civil Engineering and Building Technology, 2008). As a factor affecting the performance of the radar detector, the detection rate due to a vehicle's driving speed gradually decreased from 50 km/h before rapidly decreasing from 30 km/h or less(Jang *et al*., 2005). Furthermore, the height of the radar detector should increase as the gap spacing decreases to reduce traffic volume errors. Currently, the proper height for a radar detector monitoring a heavily congested roadway is 12–21 m(Ko *et al*., 2015).

The detector error type is divided into undetected and overdetected varieties as shown in previous studies on the improvement of radar detector performance(Choi, 2010; Korea Institute of Civil Engineering and Building Technology, 2008). Undetected traffic volume is a characteristic that arises in general vehicle detectors, and overdetection arises in radar detectors only. The latter occurs when one large vehicle attempts to change lanes within the detection area of all lanes observed by a radar detector installed external to the road. In this instance, the vehicle is detected as two different vehicles passing through two detection areas. The undetected error type is caused by a variety of factors, such as problems in the radio wave output, an algorithm error, abnormal vehicle driving, the occurrence of an undetectable shaded area caused by a large vehicle, and the detection of two vehicles as one due to low-speed driving. Traffic data collected using advanced equipment are subject to error for various reasons, including the roadway environment, collection equipment, and road geometry. It is difficult to quantitatively analyze the cause of traffic volume by counting errors because several of these factors can occur in combination.

According to existing studies, factors influencing detector performance were derived from vehicle gap spacing, vehicle speed, detector height, large vehicle operation frequency, and vehicle operation behavior. However, no studies have statistically analyzed specific factors that deteriorate detector performance or have identified solutions to detection errors caused by complex factors. Furthermore, the performance evaluation of radar detectors has been conducted by including various types to emphasize the superiority of one particular detector, and other studies evaluated detection rate using field experiments. These methods are limited in terms of deriving quantitative analysis results related to the error factors of traffic volume counting by detectors other than fragmentary improvement alternatives such as detector relocation and system tuning. Accordingly, the present study aims to derive quantitative analysis results regarding the causal relationship between the traffic volume of radar detectors and various factors that have not been reviewed statistically to date.

## 3. Methodology

### 3.1. Radar detector traffic volume error analysis model

This study assumes that the multiple linear regression model is the best model among various analysis models. This is because the main purpose of this study is to analyze the linear relationship between the dependent variable and the independent variables, and to verify the significance and influence of the independent variables affecting the dependent variable.

In general, when a traffic volume prediction model is developed by applying a MLR (Multiple Linear Regression) model, the causal relationship of the independent variable to the dependent variable can statistically be well explained(Mohamad *et al*., 1998). That is, MLR analysis is a method of statistically measuring the impact analysis between one dependent variable and several independent variables, hypothetical experiments, and factor analysis modeling(Kim, 2018). Importantly, selecting an appropriate independent variable when developing a radar detector traffic error analysis measure using an MLR model is important for addressing such problems as doing so will help in supporting the independent variable and the multicollinearity caused by the inclusion of unnecessary independent variables in the model(Choi *et al*., 2012). To diagnose multicollinearity, VIF (Variance Inflation Factor) and tolerance limits are commonly used. If the VIF is greater than ten and the tolerance limit is less than 0.1, it can be anticipated that a multicollinearity problem will arise(Kim and Kim, 2017).

### 3.2. Model verification method

In this study, two indicators were selected for the validation of the radar detector error analysis model.

First, the total volume error rate was compared for three types of traffic volumes, i.e., the video traffic volume, the radar detector traffic volume, and the traffic volume as predicted using the MLR model. The radar detector traffic volume may include errors, either undetected or overdetected error types, caused by several factors during the collection process. This study evaluated the prediction accuracy of the MLR model by comparing the traffic volume collected over 24h using Eq. (1) below:

$$Total\ Volume\ Error\ Rate\ (\%) = \left| \left( \frac{\sum \hat{y} - \sum y}{\sum y} \right) \right| \times 100 \quad (1)$$

Where $y$ is the video traffic volume, and $\hat{y}$ is the radar detector traffic volume or predicted traffic volume.

Second, the RMSE (Root Mean Squared Error) was applied to verify the accuracy of the radar detector traffic prediction model. The RMSE is an index representing the difference between the observed traffic volume and the predicted traffic volume using the MLR model as shown in Eq. (2). The smaller the RMSE value is, the better the model could be evaluated.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (2)$$

Where $y_i$ is the video traffic volume, $\hat{y}_i$ is the radar detector traffic volume or predicted traffic volume, and $n$ is number of samples.

# 4. Study data

## 4.1. Site selection

This study targeted 36 radar detectors installed at road sections in Incheon Metropolitan City, South Korea (Fig. 2). The following considerations were included: radar detectors could include different error types because they detected all traffic volume in multilane two-way roads, and one installation was external to the roadway. Thus, 36 sites were classified by vehicle driving direction, and a total of 72 sites were selected for analysis.

Radar Detector Site

| No. | Site | Coordinate | |
|---|---|---|---|
| | | X | Y |
| 1 | VDR0018 | 37.4505 | 126.7078 |
| 2 | VDR0306 | 37.4099 | 126.7130 |
| 3 | VDR0604 | 37.4478 | 126.7433 |
| 4 | VDR0203 | 37.5261 | 126.7516 |
| 5 | VDR0801 | 37.5439 | 126.7418 |
| 6 | VDR0014 | 37.4491 | 126.7204 |
| 7 | VDR0017 | 37.4401 | 126.7063 |
| 8 | VDR0406 | 37.4381 | 126.7065 |
| 9 | VDR0202 | 37.4599 | 126.7199 |
| 10 | VDR0506 | 37.4828 | 126.6788 |
| 11 | VDR1003 | 37.4029 | 126.6797 |
| 12 | VDR1101 | 37.5938 | 126.6536 |
| 13 | VDR0105 | 37.4864 | 126.6590 |
| 14 | VDR0106 | 37.4852 | 126.6632 |
| 15 | VDR1704 | 37.5305 | 126.7465 |
| 16 | VDR1710 | 37.4503 | 126.7449 |
| 17 | VDR1806 | 37.4499 | 126.7067 |
| 18 | VDR0002 | 37.4568 | 126.6895 |
| 19 | VDR0206 | 37.4507 | 126.6916 |
| 20 | VDR0501 | 37.4495 | 126.6798 |
| 21 | VDR0006 | 37.4495 | 126.6798 |
| 22 | VDR1716 | 37.4743 | 126.6919 |
| 23 | VDR1707 | 37.4232 | 126.7097 |
| 24 | VDR0301 | 37.4350 | 126.6973 |
| 25 | VDR0309 | 37.4073 | 126.6842 |
| 26 | VDR0309 | 37.3974 | 126.7064 |
| 27 | VDR0407 | 37.3988 | 126.7064 |
| 28 | VDR1103 | 37.5927 | 126.6581 |
| 29 | VDR1104 | 37.5865 | 126.6609 |
| 30 | VDR1501 | 37.5798 | 126.6628 |
| 31 | VDR1601 | 37.5934 | 126.6982 |
| 32 | VDR0103 | 37.5927 | 126.6994 |
| 33 | VDR0703 | 37.4831 | 126.6596 |
| 34 | VDR0704 | 37.4489 | 126.6267 |
| 35 | VDR1705 | 37.5527 | 126.6656 |
| 36 | VDR1701 | 37.4450 | 126.6516 |

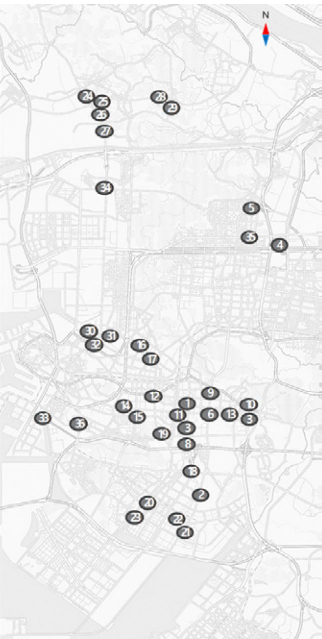


**Fig. 2. Survey Sites**

## 4.2. Data collection

In this study, traffic volume data were divided into two types, i.e., radar detector traffic volume and video traffic volume. The former is represented by Incheon Metropolitan City Traffic Information Center data collected every 15 min from 2015 to 2019. The video traffic volume is represented by video camera-recorded data for only one day among Tuesday, Wednesday, and Thursday in October from 2015 to 2019. In this study, traffic volume collected from 2015 to 2018 was used to develop a radar detector traffic error analysis model, and the traffic volume collected in 2019 was used to verify the prediction accuracy of the model. The traffic volume collected through radar detectors included errors caused by various factors. To consider the factors that caused these errors, this study collected variables such as radar detector characteristics, road facilities and geometry characteristics, and traffic environment details.

## 4.3. Radar detector traffic volume error types

This study analyzed traffic volume error types by comparing the radar detector traffic volume and the video traffic volume in the same time-step. Figs. 3(a), 3(b) and 3(c) show the results of the representative error types of the radar detector traffic volume(artificial, mechanical, and complex errors).

Artificial errors(Fig. 3(a) Type I) were caused by the disappearance of lanes in the detection area, and these were the result of physical causes such as illegal parking and stopping. After reviewing the video camera data, these artificial errors were confirmed to have occurred because of illegal parking and vehicles stopping at all sites at the time that the detection error occurred. This error was characterized by a clear difference between the radar detector traffic volume and the video traffic volume at the time when the radar detector was disturbed. Mechanical errors(Fig. 3(b) Type II), caused by malfunctioning of the radar detector, showed a remarkable difference between the radar detector traffic volume and the video traffic volume despite the lack of any physical obstacle factors(e.g., illegal parking and stopping in the detection site). Because these phenomena occurred irrespective of a specific date, they can be considered mechanical errors. The artificial and mechanical errors are detection error types that can be directly observed and are characterized by having a clear cause. When these errors are detected, the radar detector traffic volume can be corrected by applying a method that inputs past recorded traffic volume for the same time(Kim

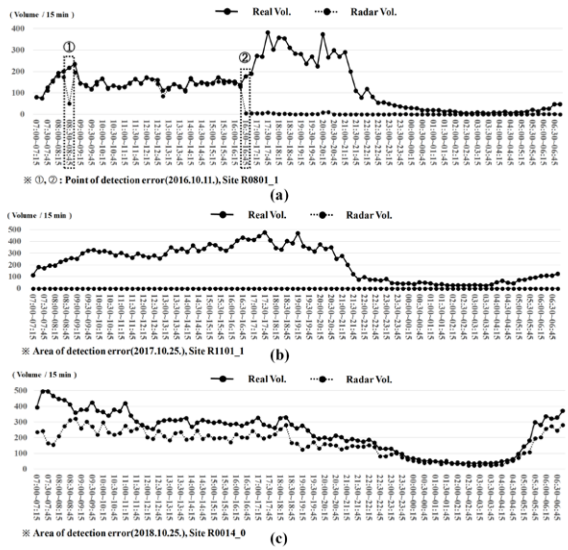



**Fig. 3. Radar detector traffic volume error types : (a) Type Ⅰ, (b) Type Ⅱ, (c) Type Ⅲ**

*et al*., 2010; Zhong and Sharma, 2009; Lee and Shin, 2013). However, when the complex error type(Fig. 3(c) Type III) occurs because of a combination of various factors other than artificial and mechanical detection errors, establishing a standard for imputing past data can be difficult.

## 5. Results

### 5.1. Relationship analysis between the radar detector traffic volume and various factors

To develop the radar detector traffic volume error analysis model, several factors must be considered when selecting independent variables. This indicates that the radar detector traffic volume may cause an error depending on the relationship between vehicle driving speed and the real traffic volume on a roadway(Ko *et al*., 2015; Choi, 2010). Urban roadways include road sections and signal intersections. Therefore, near a stop line at a signal intersection, vehicle driving speed will change significantly according to the signal change. Furthermore, this specific site type is subject to sensitive changes in V/C ratio (Volume / Capacity), vehicle gap spacing, and the number of lane changes based on various traffic facilities installed between the stop line and the radar detector. The present study comprised a total of 47 variables, such as driveway, bus stops, and crosswalks, based on the location where the detector was installed. However, the vehicle type ratio is an important variable that can also affect the results of traffic volume collected by radar detectors, but this aspect was excluded from this study because the radar detector collected traffic volume according to an arbitrary vehicle length set by the system designer. As such, it was difficult to accurately classify vehicle type. Additionally, this study analyzed the relationship between the collected variables and the radar detector traffic volume using Pearson's correlation coefficient. In the correlation analysis between radar detector traffic volume and the independent variables, 45 variables(P-value $<$ 0.05) showing a confidence level significance of 95 % or more were selected among a total of 47 variables. However, the driveway (P-value = 0.847) and central exclusive bus lane(P-value = 0.906) variables were analyzed as statistically insignificant variables. Among the statistically significant independent variables, the video traffic volume variable showed the highest correlation with radar detector traffic volume(Pearson = 0.871). In addition, the number of lanes (Pearson = 0.236), lane width(Pearson = 0.236), roadway length(Pearson = 0.102), bus lane operation time(Pearson = -0.136), bus-stop presence(Pearson = 0.202), number of bus stops(Pearson = 0.123), enforcement camera(Pearson = 0.107), and peak hours(mornings, Pearson = -0.171; or evenings, Pearson = -0.141) showed relatively high correlation with dependent variables compared with other independent variables.

### 5.2. Model development

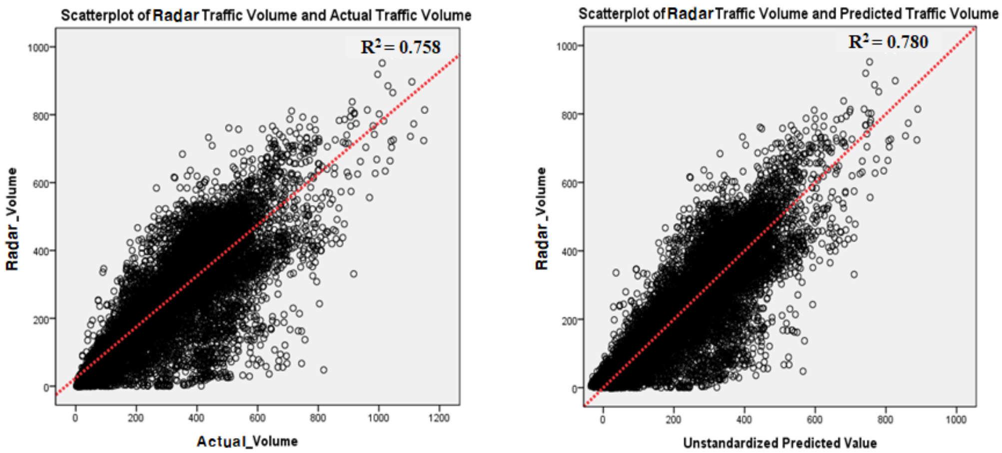
This study used the IBM SPSS Statistics 20 software package to develop a radar detector traffic error analysis model. The correlation between the dependent and independent variables was selected within the 95% confidence level(t = 1.96). The independent variable of the final model was selected by applying the forward selection method, which is a method of sequentially adding independent variables with high correlation coefficient values. In addition, this study analyzed the independence of variables through multicollinearity diagnosis and Durbin-Watson test. A multicollinearity diagnosis was performed using VIF to select independent variables that influenced the dependent variable. The developed radar detector traffic error analysis model results and the basic statistics of independent variables included in this model are shown in Table 1. A total of 13 indepen-

**Table 1. The results of the radar detector traffic error analysis model**

| | Variables | | | Statistics | | | | MLR | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | Aver. | Std. Err. | Coeff. | Std. Err. | t-value | P-value | VIF |
| | Constant | | | - | | | | -40.636 | 7.452 | -5.453 | 0.000 | - |
| **Volume** | Video Traffic Volume [vol/15 min] | | X1 | 2 | 1,151 | 258.6 | 174.9 | 0.741 | 0.003 | 249.047 | 0.000 | 1.089 |
| **Radar Detector Characteristics** | Installation Adjacent Roadway [yes = 1, no = 0] | | X2 | 0 | 1 | 0.51 | 0.50 | 7.662 | 1.104 | 6.940 | 0.000 | 1.224 |
| | Height of Radar Detector [m] | | X3 | 3.3 | 7.3 | 4.23 | 0.77 | -0.088 | 0.009 | -10.077 | 0.000 | 1.838 |
| | Radar–VMS* Installation [yes = 1, no = 0] | | X4 | 0 | 1 | 0.17 | 0.38 | -17.354 | 1.376 | -12.609 | 0.000 | 1.082 |
| **Geometry** | Number of Lanes | | X5 | 2 | 6 | 3.72 | 0.81 | 13.159 | 0.657 | 20.035 | 0.000 | 1.143 |
| | Horizontal alignment | Left Curve [yes = 1, other = 0] | X6 | 0 | 1 | 0.08 | 0.27 | -35.417 | 2.099 | -16.873 | 0.000 | 1.247 |
| | | Right Curve [yes = 1, other = 0] | X7 | 0 | 1 | 0.08 | 0.27 | -19.486 | 2.153 | -9.052 | 0.000 | 1.307 |
| | Vertical alignment | (+) Grade [yes = 1, other = 0] | X8 | 0 | 1 | 0.08 | 0.27 | -14.592 | 2.142 | -6.812 | 0.000 | 1.299 |
| | | (−) Grade [yes = 1, other = 0] | X9 | 0 | 1 | 0.09 | 0.28 | -5.819 | 2.092 | -2.782 | 0.005 | 1.378 |
| **Traffic Environment** | Number of driveways | | X10 | 0 | 10 | 1.41 | 2.03 | -1.345 | 0.284 | -4.737 | 0.000 | 1.338 |
| | Bus Lane Operation Hour [yes = 1, no = 0] | | X11 | 0 | 1 | 0.03 | 0.17 | -9.187 | 3.050 | -3.012 | 0.003 | 1.080 |
| | Speed Limit [km/h] | | X12 | 30 | 60 | 59.14 | 4.99 | 1.077 | 0.104 | 10.398 | 0.000 | 1.077 |
| | Speed Camera [yes = 1, no = 0] | | X13 | 0 | 1 | 0.03 | 0.18 | -12.590 | 3.392 | -3.712 | 0.000 | 1.490 |
| $R^2$ | | | | 0.7803 | | | | | | | | |
| Adjusted-$R^2$ | | | | 0.7802 | | | | | | | | |
| Durbin-Watson** | | | | 2.110 | | | | | | | | |
| N | | | | 20,160 | | | | | | | | |

Note: * means that Radar detector and VMS (Variable Message Signs) are installed together.

** No autocorrelation DW → 2, Sever positive autocorrelation DW → 0, Sever negative autocorrelation DW → 4




(a) (b)

**Fig. 4. A scatterplot of video and the created model's prediction traffic volume compared with the radar detector traffic volume : (a) Scatterplot of Radar Traffic Volume and Actual Traffic Volume, (b) Scatterplot of Radar Traffic Volume and Predicted Traffic Volume**

dent variables were selected, including video camera traffic volume, radar detector installation characteristics, road geometry, and traffic environment as factors affecting the radar detector traffic volume. Durbin-Watson test and multicollinearity diagnosis were performed for these variables. The results showed that Durbin-Watson was analyzed as 2.110 and the VIF was less than ten in all independent variables. Additionally, the analysis showed no problems related to multicollinearity. This study adopted the adjusted-$R^2$ as a useful criterion for gauging the model goodness of fit. The adjusted-$R^2$ of this model was 0.78, which indicated that the 13 significant factors of the model explained approximately 78 % of the variability in radar detector traffic volume. As shown in Figs. 4(a) and 4(b), this study compared adjusted-$R^2$ in two cases. First, the adjusted-$R^2$ between the radar detector traffic volume and video traffic volume was analyzed and found to be 0.758(Fig. 4(a)). Thus, a positive linear relationship was found between the two volume types. This indicated that the correlation between radar detector traffic volume and video traffic volume was high. Second, the adjusted-$R^2$ between the radar detector traffic volume and the model's predicted volume was analyzed and found to be 0.780(Fig. 4(b)). Accordingly, a positive linear relationship existed between these two volume types. This indicated that the model's prediction accuracy was further increased when independent variables affecting the radar detector traffic volume were added to the video traffic volume.

### 5.3. Model validation

The verification method of the radar detector traffic error analysis model in this study compared the total volume error rate and RMSE for the predicted traffic volume, radar detector traffic volume, and video traffic volume. The verification data used traffic volume from 2019, which was not used for model development. Additionally, among 72 sites selected for model development, 30 targeted sites were included, excluding sites where radar detector replacement and traffic volume collection errors occurred in 2019. Table 2 shows the results of the radar detector traffic error analysis model verification. In this study, two indicators were selected for the validation of the radar detector error analysis model. Several aspects related to the above results should be considered. The result of comparing the accumulated total volume error rate for 24 h can be analyzed as having improved the radar detector's problem of under or overcounting through the application of the established model. However, this may have been the result of offsetting errors in the traffic volume, which was collected every 15 min. For this reason, this study analyzed also the RMSE, considering the variability of traffic volume every 15 min.

**Table 2. Results of the radar detector traffic error analysis model verification**

| No. | Site | Real Vol. | Radar Vol. | MLR Vol. | Total Vol. Error | | RMSE* | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Diff. Radar-Real | Diff. MLR-Real | Radar-Real | MLR-Real |
| 1 | R0014_0 | 23,115 | 17,869 | 21,409 | 22.7% | 7.4% | 115.2 | 51.4 |
| 2 | R0014_1 | 19,801 | 11,358 | 16,711 | 42.6% | 15.6% | 133.5 | 57.4 |
| 3 | R0017_0 | 12,100 | 10,902 | 13,013 | 9.9% | 7.5% | 26.8 | 25.0 |
| 4 | R0017_1 | 11,558 | 11,052 | 12,141 | 4.4% | 5.0% | 22.0 | 23.9 |
| 5 | R0018_0 | 37,679 | 26,819 | 34,360 | 28.8% | 8.8% | 135.6 | 77.2 |
| 6 | R0018_1 | 48,637 | 29,534 | 43,099 | 39.3% | 11.4% | 224.0 | 88.6 |
| 7 | R0105_0 | 28,237 | 25,944 | 29,579 | 8.1% | 4.8% | 50.2 | 41.0 |
| 8 | R0105_1 | 28,981 | 27,394 | 29,951 | 5.5% | 3.3% | 36.6 | 30.8 |
| 9 | R0106_0 | 37,297 | 27,659 | 35,285 | 25.8% | 5.4% | 133.3 | 48.1 |
| 10 | R0106_1 | 39,884 | 25,831 | 38,321 | 35.2% | 3.9% | 174.4 | 46.5 |
| 11 | R0202_0 | 26,384 | 21,248 | 26,441 | 19.5% | 0.2% | 93.5 | 39.7 |
| 12 | R0202_1 | 23,516 | 19,046 | 21,794 | 19.0% | 7.3% | 71.5 | 40.1 |
| 13 | R0203_0 | 27,910 | 20,632 | 26,057 | 26.1% | 6.6% | 101.2 | 56.8 |
| 14 | R0203_1 | 26,489 | 30,917 | 32,804 | 16.7% | 23.8% | 65.0 | 86.3 |
| 15 | R0306_0 | 24,089 | 20,697 | 23,097 | 14.1% | 4.1% | 54.9 | 34.2 |
| 16 | R0306_1 | 27,351 | 25,284 | 27,531 | 7.6% | 0.7% | 34.8 | 30.4 |
| 17 | R0406_0 | 34,430 | 30,724 | 34,392 | 10.8% | 0.1% | 57.1 | 37.5 |
| 18 | R0406_1 | 35,771 | 31,230 | 35,064 | 12.7% | 2.0% | 59.8 | 33.3 |
| 19 | R0506_0 | 35,989 | 36,070 | 39,547 | 0.2% | 9.9% | 28.9 | 66.6 |
| 20 | R0506_1 | 35,216 | 34,677 | 37,040 | 1.5% | 5.2% | 31.1 | 49.7 |
| 21 | R0604_0 | 14,811 | 13,483 | 14,557 | 9.0% | 1.7% | 27.6 | 25.0 |
| 22 | R0604_1 | 15,035 | 14,737 | 15,039 | 2.0% | 0.0% | 18.3 | 22.8 |
| 23 | R0801_0 | 10,523 | 9,797 | 11,980 | 6.9% | 13.9% | 20.7 | 28.6 |
| 24 | R0801_1 | 11,073 | 9,680 | 11,942 | 12.6% | 7.8% | 35.8 | 26.5 |
| 25 | R1003_0 | 27,333 | 571 | 21,533 | 97.9% | 21.2% | 313.3 | 80.8 |
| 26 | R1003_1 | 26,237 | 18,734 | 22,744 | 28.6% | 13.3% | 104.7 | 55.8 |
| 27 | R1101_0 | 20,624 | 232 | 12,984 | 98.9% | 37.0% | 256.4 | 108.6 |
| 28 | R1101_1 | 19,511 | 7,719 | 13,555 | 60.4% | 30.5% | 163.0 | 93.6 |
| 29 | R1704_0 | 15,331 | 19,570 | 22,411 | 27.6% | 46.2% | 68.9 | 93.7 |
| 30 | R1704_1 | 16,669 | 23,461 | 24,498 | 40.7% | 47.0% | 80.8 | 107.9 |
| Average Difference | | | | | 24.5% | 11.7% | 91.30 | 53.6 |

Note: * "RMSE = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}$, $y_i$ is the 15 min video traffic volume, $\hat{y}_i$ is the 15 min radar detector traffic volume or MLR predicted traffic volume, and $n$ is number of samples (24 hours/15 minutes = 96).

The analysis of the total volume error rate revealed that the LSTM–MLR hybrid model reduced the error rate at 23 out of 30 sites. The average total volume error rate was reduced by 12.8 %p from 24.5 % for radar detector traffic volume to 11.7 % for predicted traffic volume. In addition, the RMSE analysis revealed that the MLR model reduced the error rate at 22 sites out of 30. The RMSEs of the detector traffic volume and the predicted traffic volume were 91.3 and 53.6, respectively. As a result of the analysis, it was analyzed that both indicates that there is a correction effect on the traffic volume of the radar detector through the MLR model.

### 5.4. Factor analysis

As shown in Table 1, this study analyzed the causal relationship between radar detector traffic volume and various factors that can cause errors based on the following results yielded by the developed model.

The video traffic volume variable was photographed using a video device at the same site where the radar detector was installed. As the video traffic volume increased, the radar detector traffic volume also increased. As this video traffic volume increased, the radar detector traffic volume also increased.

The radar detector adjacent roadway variable was analyzed, and it indicated that the traffic volume of the road section installed adjacent to the radar detector had been counted more compared with the opposite direction lane. This happened because large vehicles created areas that were not detected, and these areas were more frequently interfered with by large cars as they moved away from the detector.

In this study, the height of radar detector variable was analyzed and showed that the higher the radar is, the smaller the detector traffic volume is. This result was assumed to have occurred owing to the undercounting of the detected traffic volume because the detector height was lower than the appropriate height. Generally, the optimal height for the placement of the radar detector is calculated using the distance to the first detection lane close to the pole where the detector is installed or using the relationship between the total number of detection lanes and the radar placement height. A previous experiment indicated that the shorter the gap spacing between vehicles is, the higher the installation height of the detector should be, from 3 to 19 m, based on a mid-size vehicle(Zang *et al*., 2005). However, the radar detectors collected in this study were installed at a minimum height of 3.3 m and a maximum of 7.3 m(average, 4.2 m).

The radar–VMS installation variable was analyzed, and it showed that when the detector was installed together with the VMS, the detected traffic volume was less than when it was installed on its own. In general, VMS is installed and operated at roadways where traffic congestion frequently occurs(Ministry of Land, Infrastructure and Transport, 2016). Therefore, a site where a detector and VMS are installed together will be a high-traffic roadway. In such congested traffic situations, radar detector errors occur in the process of separating two vehicles running continuously because the gap spacing between vehicles shortens as the vehicle speed decreases(Ryu *et al*., 1998).

Generally, roadway capacity and traffic volume on urban roadways indicated a positive correlation in terms of traffic volume and road investment. In this regard, the number of lanes variable was analyzed to increase the radar detector traffic volume as the number of lanes increases.

The horizontal alignment and vertical alignment variables were analyzed to reduce the traffic volume of radar detectors. The radar detector traffic volume was found to have been reduced for a detector installed in horizontal alignment curved to the left or right of the vehicle driving direction and the vertical alignment of the (+) or (-) grade. These results can be found in a study that analyzed the relationship between road linearity and driving speed (Jo *et al*., 2010). In this study, the driving speed decreased as the grade increased or the rate of change in the horizontal curve increased.

The number of driveways variable found that the higher the number of driveways to the stop line at a signal intersection in a site where a detector was installed, the less traffic volume was detected. This was because the detection rate was lowered because of local traffic congestion caused by the frequent entry and exit of vehicles from/into driveways.

The bus lane operation hour variable was analyzed, and it showed that the radar detector traffic volume decreased during the bus lane operating hours. This happened because some lanes could not be detected because of frequent bus traffic during the bus lane operating hours(07:00–09:00 and 17:00–20:00).

The speed limit variable analysis found that the higher the speed limit is, the greater the radar detector traffic volume is. In general, a roadway with a high-speed limit will be an urban arterial roadway supporting significant traffic volume. The analysis indicated that the radar detector traffic volume increased in the case of a roadway with high-speed limits.

The speed camera variable showed, however, that the traffic volume measured by the traffic radar detector decreased in a roadway where a speed camera had been installed. The analysis indicated that the radar detector traffic volume had been reduced because of the low and constant speed of vehicles using the roadway where a speed camera had been installed, e.g., in a school zone.

## 6. Conclusions

High-tech equipment has been employed to collect traffic data. The radar detector market is expanding and presents advantages such as saving maintenance costs, easy installation, few obstacles in the data aggregation process, and the accuracy of collected data. Radar is a versatile technology that is applied in a broad range of fields, such as autonomous vehicles and small drones. However, radar detector traffic data can at times exclude and incorrectly detect data, and it can be difficult to determine why this happens. To solve these problems, this study developed a model for analyzing the traffic volume errors of radar detectors and presented the results of the quantitative analysis on the effects of radar detector characteristics, road facilities and geometry, and other traffic environment factors. A radar detector traffic volume error analysis model(adjusted $R^2$ = 0.78) was developed using an MLR model for radar detectors installed and operated in Incheon Metropolitan City, South Korea. A total of 13 independent factors were selected as statistically significant variables. Among these variables, the independent variables that were positively related to the traffic volume of the radar detectors were video traffic volume, radar detector adjacent roadway, the number of vehicle lanes, and speed limit. Contrastingly, the independent variables that were negatively related to the traffic volume of the radar detectors were analyzed based on the height of the radar detector, radar–VMS installation, horizontal alignment (curved to the left or right of the vehicle driving direction), vertical alignment ((+) or (−) grade), number of driveways, exclusive bus lane operation hours, and the presence of speed cameras. Finally, this study applied an MLR model to analyze the causal relationship between the radar detector traffic volume and several factors. Importantly, future research requires a detailed analysis of the causes of the errors made by radar detectors in each specific traffic volume area as it concerns radar detector and video data. In addition, the prediction accuracy of the MLR model developed in this study was verified using the actual traffic volume. Recently, the prediction ability of time series data has been improved by using algorithms such as machine learning. Therefore, additional validation of the MLR model through these algorithms is required.

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