Estimation of Snow Removal Operation Effects Using a Travel Speed Prediction Model

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Abstract: Winter weather conditions, such as snowfall, deep snow, and low temperatures, affect traffic conditions. Therefore, the objective of this study is to develop a method for estimating the effects of snow removal operations on travel time using the RegARIMA travel speed prediction model, in order to reduce winter traffic congestion. The predictive accuracy of the RegARIMA was compared with the univariate ARIMA under different weather conditions: snow versus non-snow conditions. The effects of snow removal operations conducted independently and in several combinations during a certain period based on four scenarios were estimated. Snow hauling was found to have the greatest travel time-saving effects, and the effect of fresh snow removal operation was the smallest. The proposed methodology might be used for forecasting traffic congestion on urban arterials in winter and for improving winter urban road maintenance strategies.

Keywords: Travel Speed Prediction, Snow Removal, Winter Road Maintenance, Effect Estimation, Time-Series Model

1. INTRODUCTION

Winter weather conditions, such as snowfall, deep snow, and low temperatures, affect traffic conditions. Many previous researchers (Agarwal *et al.*, 2005; Maze *et al.*, 2006; Dehman, 2012; Zhao *et al.*, 2012; Kwon *et al.*, 2013; Lin *et al.*, 2015; Hong *et al.*, 2015) have demonstrated the relationships between the traffic conditions and weather factors including rainfall, snowfall, fog, wind, and temperature. Previous research found that traffic speed decreases with increase in the intensity of rainfall and snowfall. As in the previous results, the travel speed in Sapporo is about 10 km/h slower in winter than in autumn (Hong *et al.*, 2015).

To reduce traffic congestion in winter, the City of Sapporo performs four kinds of snow removal operations using various kinds of equipment: fresh snow removal, road surface leveling, widening of the effective road width (road widening), and snow hauling. These are performed based on the threshold for snow removal deployment set by the City of Sapporo (2016). The levels were set according to the number of lanes the road has. For example, 6-lane arterials are maintained to 4 lanes in winter, and 4-lane arterials are maintained to 3 lanes in winter. In other words, although snow removal from the carriageway by plowing can achieve a snow-free road surface, such removal can reduce the number of effective lanes in winter. And the decrease in effective road width leads to reduced traffic performance, in terms of speed, volume, and capacity. However, few studies on snow removal (Lin, 2008; Koizumi and Naoi, 2012) have addressed the value of snow removal based on questionnaire surveys from residents, and they have not quantified the effects of snow removal on traffic performances.

The present study aims to develop an analysis method for quantifying snow removal effects using a travel speed prediction model that is a regression model with autoregressive integrated moving average time-series errors (a RegARIMA model). As mentioned above, the travel speed in winter is affected by snow removal operations. Therefore, the effects of snow removal operations can be estimated by the changes in traffic performance resulting from those operations. While many previous researchers (Wu *et al.*, 2004; Billings and Yang, 2006; Lee *et al.*, 2006; Vlahogianni and Karlaftis, 2012; Zhang and Ge, 2013; Wang *et al.*, 2015; Kim *et al.*, 2015) have developed prediction models for travel speed or travel time using various methodologies, few researchers have considered adverse weather conditions in their speed prediction models (Vlahogianni and Karlaftis, 2012; Hong *et al.*, 2015; Kim *et al.*, 2015).

To develop a travel speed prediction model, field data of weather conditions, traffic conditions, and snow removal operations need to be collected. Cyber-physical systems (CPSs) are smart systems that collect and analyze real-world data from advanced sensors to solve problems, after which the results are fed back to the real-world in a continuous cycle (Japan Electronic and Information Technology Industries Association (JEITA), 2016). In the present study, three kinds of real-world data are collected and transformed into computerized data: traffic data, weather data and snow removal data. These data were input into statistical models in order to estimate travel speed. The results of the present study could be helpful in the development of new strategies for winter traffic control and for snow removal operations. Therefore, the present study can be expected to contribute to the realization of a CPS society which optimizes the physical world by controlling everything that is interconnected in the physical world, including people, vehicles and houses.

2. DATA COLLECTION

The current study selected a 4.8-km segment of Tarukawa Dori (an urban arterial) from JR Sapporo Station to the Asabu Subway Station as the study area (Figure 1). That area was divided into 10 sections demarcated by major intersections, and each section was separated by direction: northbound versus southbound. The links (S1 and N10) at both ends of the study route were not included in the analysis because the traffic data were collected at intersections from 1 to 9 in Figure 1. In other words, the study area consists of 18 links. The length of each section is presented in Table 1. This route is a main street that connects the central commercial/business district of Sapporo to residential areas north of that district.

The weather condition data were collected by the Automated Meteorological Data Acquisition System (AMeDAS) of Sapporo. The AMeDAS station in Sapporo is about 1.8 km from JR Sapporo Station and 5.6 km from the Asabu Subway Station (Figure 1). The present study assumes that the weather conditions are same at the AMeDAS station and in the study area. Among the weather data, the air temperature, snowfall, and deep snow, was considered for the analysis.

Travel speed was collected from probe taxis in Sapporo. These data are 5-minute link-based data that include travel time, link length, geographic coordinates, and travel direction for each link. The data were aggregated into hourly data to match the interval of the weather condition data. Taxi probe data for the hours of 20:00 to 07:00 were not included in the analysis, because night taxi ridership is rare in Sapporo. The duration for analysis was the winter of 2013-2014, from 10 December 2013 to 31 March 2014. Only weekdays were used for analysis, because the traffic patterns of these periods differ from general traffic patterns. Additionally, taxis slower than preferred walking speed (1.21 mi/h = 4.356 km/h) (Mohler *et al.*, 2007) were excluded to ignore abnormally slow taxis, such as those waiting for passengers, and vehicles broken down on the road. In summary, the analysis period covered 13 hours per day for weekdays in the winter of 2013-2014 (10 December 2013 to 31 March 2014), with other times excluded from analysis.

Table 1. The link lengths

Link ID	Section	Direction	Length (km)	Link ID	Section	Direction	Length (km)
N1	1	Northbound	0.4	N6	6	Northbound	0.6
n/a		Southbound		S6		Southbound	
N2	2	Northbound	0.5	N7	7	Northbound	0.35
S2		Southbound		S7		Southbound	
N3	3	Northbound	0.4	N8	8	Northbound	0.8
S3		Southbound		S8		Southbound	
N4	4	Northbound	0.4	N9	9	Northbound	0.35
S4		Southbound		S9		Southbound	
N5	5	Northbound	0.4	n/a	10	Northbound	0.6
S5		Southbound		S10		Southbound	
Whole section (km)				4.8			

Figure 1. Study area and AMeDAS station

As mentioned above, four kinds of snow removal operations are performed on roads in Sapporo: fresh snow removal, road surface leveling, widening of the effective road width, and snow hauling. Road snow removal operations in Sapporo are conducted such as to complete such removal in the 6 hours from midnight to 6 a.m. In fresh snow removal operations, newly fallen snow is pushed to the shoulders. The fresh snow removal affects traffic in two opposite ways. This operation can maintain the roads in good condition by removing newly fallen snow on the road surface. However, the effective road width is narrowed when the snow is pushed to the shoulders. In leveling operations, graders flatten rough roads. In road widening operations, the effective width of roads that have been narrowed by fresh snow removal is increased. In snow hauling, piled snow is hauled to disposal sites. Fresh snow removal operations are performed when the deep snow on the road is more than 10 cm, while other operations are performed when the city deems it necessary. This study addresses the three snow removal operations other than road surface leveling.

3. VARIABLES

Travel speed collected by probe taxis was employed as the dependent variable for the model. And two groups of variables were selected as independent variables for the model: weather conditions and snow removal operations. All variables were aggregated into an hourly mean. Travel speed (km/h), temperature (℃), snowfall (cm/h) and deep snow (cm) are continuous variables.

In terms of temperature, some researchers (Asano and Hirasawa, 2003; Lee *et al.*, 2014) have studied the relationship between temperature and traffic accidents, and they have proposed that the relationship is J- or U-shaped. These results might be because the road surface at the certain range of temperatures has mixed freezing conditions, such as ice, slush, and water. For this reason, drivers feel more difficultly driving at the temperature of the minimum point on the J-curve or U-curve than at other temperature ranges. In the present study, travel speed versus temperature also plots as a U shape. Thus, the squared temperature variable ($℃^2$) is also included in the speed prediction model of the present study.

The road widening snow removal operations are expressed as the indicator variable. The road widening operation indicator was defined as “1” for links on which the effective road width was increased by road widening operation, and “0” for links on which the effective road width was decreased by fresh snow removal operation. So long as the fresh snow removal pushes snow to the shoulders, the road surface is clearer but the effective road width is narrower. Therefore, fresh removal operations are represented as both an indicator variable and a discrete variable to reflect the effects on traffic in two opposite ways. The fresh snow removal operation indicator is defined as “1” when the road surface was cleaned by fresh snow removal operation, and “0” when the road was covered with snow. And the number of fresh snow removal operations between two road widening operations was represented as a discrete variable. Lastly, snow hauling operations were not employed as an independent variable, but the effects were reflected by changes in the deep snow variable. After performing the hauling operation on a section, the deep snow variable on that section was changed to 0 cm.

4. ANALYSES AND RESULTS

The present study develops a travel speed prediction model considering weather conditions and snow removal operations. The effects of snow removal are quantified in terms of benefit from travel time reduction using the forecasted travel speed. As a travel speed prediction model, the present study employed regression with the autoregressive integrated moving average error (RegARIMA) model. Five steps are performed in estimating the effects of snow removal operations. Figure 2 shows the overall research process. The first step is to set up a dataset for analysis by combining traffic, weather, and snow removal operation data. The second step is to develop a fixed effect (FE) model, which is a linear regression model for panel data, with all the variables. The third step is to investigate the autocorrelation of the residuals between observed values and estimated values of the FE model, in order to apply ARIMA models. Then, ARIMA models are developed with the residuals, and two models of FE and ARIMA are combined. In the next step, to show the advantage of the RegARIMA model, its predictive accuracy is compared to that of the univariate ARIMA model. The last step is to estimate the effects of snow removal operations. The present study considers the effects of both individual snow removal operations and snow removal operations for a period. The effects are represented as the travel time-saving benefits. Finally, the conclusions are presented.

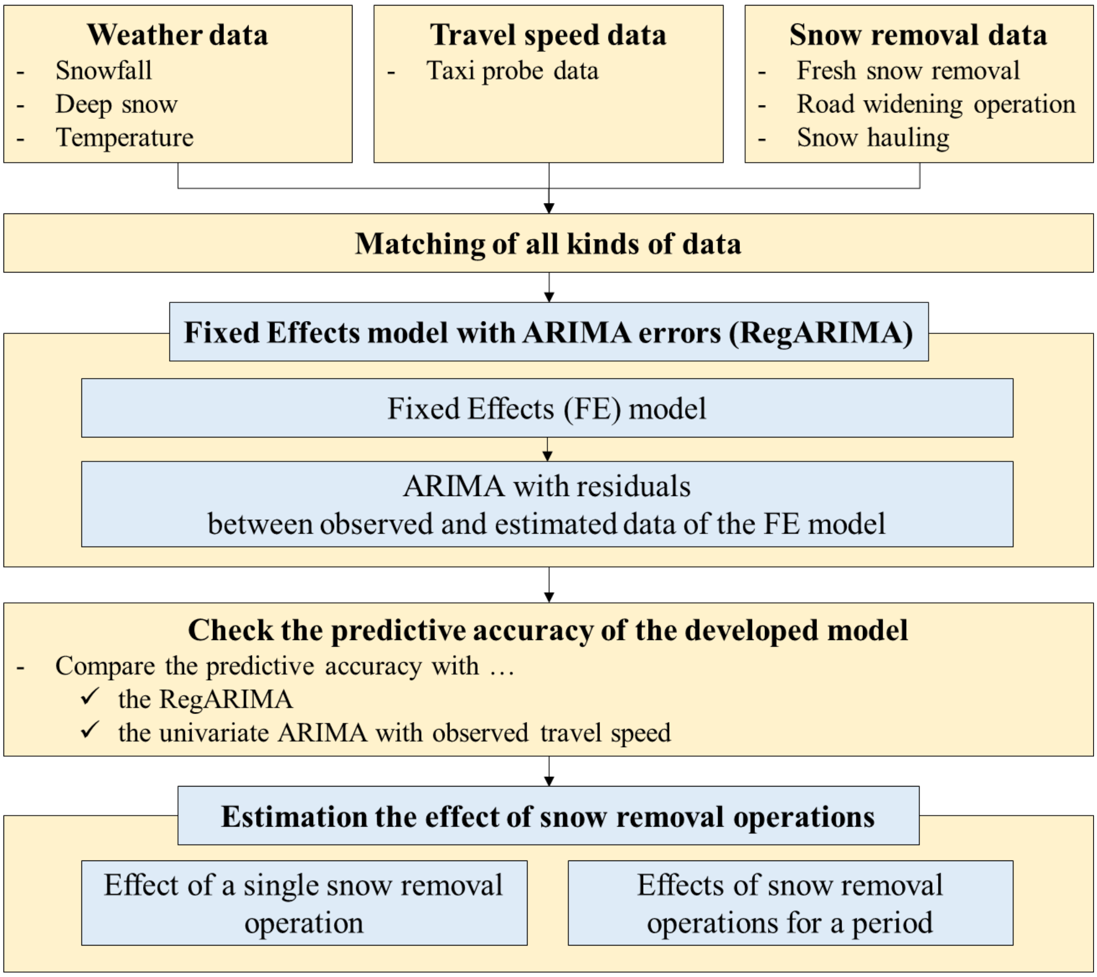

Figure 2. Research process

4.1 Regression Models with Autoregressive Integrated Moving Average Errors

A RegARIMA is the combination of a regression model and an ARIMA model (Mais *et al.*, 2016). It consists of two parts: a regression part and an ARIMA part. In ordinary least squares regressions, errors are assumed to be independent (no autocorrelation), but this assumption is commonly violated when time series data are analyzed. In RegARIMA models, the ARIMA parts account for the correlated errors. In the present study, a fixed-effects model is employed as a regression model for the RegARIMA. The model can be expressed by Equation 1.

$$y_t = \sum_{e=1}^{m} \beta_e x_{et} + \varepsilon_t \tag{1}$$

Where, y_t is the dependent variable at time point t. β_e are regression coefficients. x_{et} are independent variables. ε_t is an error term that has an ARIMA structure.

4.1.1 Fixed-effects model

An FE model is a linear regression for panel data. Panel data represent a fusion of cross-sectional data and time-series data. A panel data analysis model has some important advantages over other data models (Frees, 2004). The panel data model can control for unobserved and unmeasured variables, such as the cultural background and driving habits of drivers. Furthermore, the panel data model has less multicollinearity among independent variables than other data models have: cross-sectional data models and time-series data models. The FE model assumes that the unobserved time-invariant individual (subject) effects can be explained as the individual specific effects through intercepts. In other words, the structure of the FE model is the same as the multiple linear regression model with individual dummy variables as intercept shifters. So, it is also called the least squares dummy-variable model (LDV). However, a drawback of the FE model is that it is unable to estimate the coefficient for time-invariant effects, but these effects are included in the intercept of the model (Choi, 2008).

The FE model can be expressed as Equation 2. The dataset has 18 links (individuals) and 923 hours (duration) of information. The observed travel speed is regarded as the dependent variable, and the other variables are included as independent variables for the model.

$$\begin{aligned}(Travel\ Speed)_{it} &= \beta_1 (Temperature^2)_t + \beta_2 (Temperature)_t + \beta_3 (Snowfall)_t \\ &+ \beta_4 (Deep\ snow)_{it} + \beta_5 (Callouts\ for\ fresh\ snow\ removal)_{it} \\ &+ \beta_6 (Road\ widening)_{it} + \beta_7 (Fresh\ snow\ removal)_{it} + \mu_{it} \\ &(\mu_{it} = v_i + \varepsilon_{it})\end{aligned} \tag{2}$$

where, β_e is the regression coefficient. $(variable\ name)_{it}$ is the observed variable for the link i at the time t. μ_{it} is the error term for the link i at the time t. And the error term can be disassembled into residuals (ε_{it}) and unobserved time-invariant effects, which are represented as section-specific effects (v_i). The independent variables in FE models explain part of the dependent variable. And the leftover variation of the dependent variable, which means the dependent variable that is not explained by the independent variables, is the section-specific effect estimate.

4.1.2 Autoregressive integrated moving average model

The section-specific effects of the FE model allow the estimated travel speed to differ from link to link, so the residuals can be different across links. ARIMA models account for the residuals on each link. An ARIMA model is a general model for forecasting a time series, and a seasonal ARIMA model that is an expanded ARIMA model can be applied for periodic or seasonal time series. For example, the road tends to be crowded with commuters at morning and evening peak times on weekdays, and this occurs periodically.

The seasonal ARIMA model is used to explain the residuals (ε_{it}) from the FE model in the present study, and the seasonal ARIMA, $\text{ARIMA}(p, d, q)(P, D, Q)_S$, can be written as Equation 3.

$$\phi_p(B)(1-B)^d \Phi_P(B^s)(1-B^s)^D \varepsilon_t = \theta_q(B)\Theta_Q(B^s)u_t \quad (3)$$

Where, d and D are the number of non-seasonal and seasonal differences. $\emptyset_p(\mathrm{B})$ and $\theta_q(B)$ represent an autoregressive (AR) operator of order p and a moving average (MA) operator of order q. ε_t is the residual in Equation 2, and u_t is independent and identically distributed random variable. B is a backshift operator. $\Phi_P(B^s)$ and $\Theta_Q(B^s)$ express the seasonal AR operator of order P and the seasonal MA operator of order Q, respectively. S is the cycle length. The cycle length is 13 hours in the present study: from 07:00 to 20:00.

4.1.3 Results

The results of the FE, the ARIMA part of the RegARIMA, are shown in Table 2, Table 3 and Table 4. Furthermore, the R-squared values of the RegARIMA are also presented in Table 4. In results of the FE model, the number of fresh snow removal deployments and snowfall variables were not statistically significant at the 95% confidence level, and other significant variables were selected. Both the temperature and temperature squared value correlated positively with the travel speed. This means that the relationship between the temperature and the travel speed are U-shaped in the present study. The fresh snow removal and the road widening operations had positive relationships with the travel speed. The Durbin-Watson statistic (1.13) was lower than 1.5. This indicates that the residuals of the model serially correlate with each other (Aga and Safakli, 2007). In other words, the correlated residuals should be corrected by the ARIMA. The result of the Ljung-Box test in Table 4 shows that the corrected errors between the residuals of the FE model and the ARIMA are independent. When the significance of the Ljung-Box Q value exceeds 0.05, the errors are regarded as independent of each other at the 0.05 significance level. Finally, the R-squared values of the RegARIMA on most links were greater than those of the FE model. However, the R-squared value of S10 dropped. This might be because section 10 has a 5-way intersection, unlike the other sections.

Table 2. Results of the FE Model

Variables	Estimate	t-value	p-value
Temperature^2 (°C^2)	0.01	6.02	0.00
Temperature (°C)	0.02	-2.95	0.03
Snowfall (cm)	n/a	n/a	n/a
Deep snow (cm)	-0.13	-70.39	0.00
Fresh snow removal deployments	n/a	n/a	n/a
Road widening snow removal*	0.70	-3.23	0.00
Fresh snow removal*	0.63	7.80	0.00
F-value (p-value)	1422.8 (0.00)		
R-squared	0.51		
Durbin-Watson	1.13		

** indicator variables*

Table 3. Results of the FE Model (Section-specific effects)

Link ID	Section-specific effect estimates			Link ID	Section-specific effect estimates		
	Estimate	Std. Error	t-value		Estimate	Std. Error	t-value
N1	19.02	0.18	106.87	S1	n/a	n/a	n/a
N2	26.73	0.15	179.75	S2	19.74	0.15	132.28
N3	26.81	0.15	180.21	S3	19.52	0.15	130.99
N4	23.92	0.15	160.77	S4	20.25	0.15	134.71
N5	26.05	0.15	173.42	S5	21.69	0.15	144.20
N6	18.38	0.15	122.39	S6	17.82	0.15	118.15
N7	20.86	0.15	138.47	S7	21.32	0.15	141.52
N8	20.38	0.15	135.22	S8	20.21	0.15	134.09
N9	26.61	0.15	176.50	S9	19.53	0.15	129.57
N10	n/a	n/a	n/a	S10	17.65	0.15	118.55

Table 4. Results of the ARIMA and RegARIMA Models

Link ID	ARIMA with residuals from the FE model			RegARIMA
	Model	Stationary R^2	Sig. of Ljung-Box Q	R^2
N1	ARIMA (0,1,2)(0,1,1$_{13}$	0.659	0.255	0.911
N2	ARIMA (1,1,2)(0,1,1)$_{13}$	0.658	0.389	0.779
N3	ARIMA (0,1,2)(0,1,1)$_{13}$	0.664	0.155	0.609
N4	ARIMA (2,1,1)(0,1,1)$_{13}$	0.650	0.555	0.570
N5	ARIMA (0,1,2)(0,1,1)$_{13}$	0.644	0.666	0.744
N6	ARIMA (5,1,4)(0,1,1)$_{13}$	0.623	0.371	0.804
N7	ARIMA (4,1,2)(0,1,1)$_{13}$	0.612	0.109	0.502
N8	ARIMA (1,1,1)(0,1,1)$_{13}$	0.493	0.187	0.800
N9	ARIMA (1,1,1)(0,1,1)$_{13}$	0.687	0.793	0.720
N10	n/a	n/a	n/a	n/a
S1	n/a	n/a	n/a	n/a
S2	ARIMA (1,1,2)(0,1,1)$_{13}$	0.583	0.069	0.813
S3	ARIMA (14,1,2)(0,1,1)$_{13}$	0.627	0.335	0.611
S4	ARIMA (12,1,1)(1,1,1)$_{13}$	0.616	0.498	0.708
S5	ARIMA (2,1,1)(1,1,1)$_{13}$	0.534	0.810	0.751
S6	ARIMA (12,0,7)(0,1,1)$_{13}$	0.428	0.086	0.793
S7	ARIMA (5,1,1)(0,1,1)$_{13}$	0.631	0.534	0.794
S8	ARIMA (1,1,2)(0,1,1)$_{13}$	0.611	0.300	0.690
S9	ARIMA (5,1,6)(0,1,1)$_{13}$	0.695	0.586	0.589
S10	ARIMA (0,1,1)(0,1,1)$_{13}$	0.720	0.388	0.354

4.2 Effectiveness of the RegARIMA in Winter

The travel speed predicted by the RegARIMA under two different weather conditions was compared with the univariate ARIMA results, which has only the observed travel speed data as a variable, to investigate the effectiveness of the model in winter. Two different weather conditions were selected: snow versus non-snow conditions. The period of non-snow was the three days from Mar. 25, 2014, and the period of snow was the three days from Feb. 13, 2014. During the snow period, around 20 cm of snow fell in Sapporo. The predictive accuracies of the two models were compared in terms of the mean absolute percentage errors (MAPEs) using the out-of-sample data, and the results are presented in Table 5. The RegARIMA was found to be more accurate regardless of the snow conditions. Especially, the difference of accuracy between the ARIMA and the RegARIMA was more evident under the snow condition. Furthermore, when focusing on the predictive accuracy over time, the difference in the accuracy between the two models increased substantially under snowy condition. In other words, the MAPE of ARIMA increased over time under snow conditions, and the RegARIMA was relatively stable over time regardless of weather. Therefore, the RegARIMA was more appropriate for forecasting the travel speed in winter than the ARIMA was, because it showed more stable results regardless of the snow conditions.

Table 5. ARIMA Versus RegARIMA Predictive Accuracy under Two Different Weather Conditions (MAPEs)

Link ID	Non-snow conditions		Snow conditions	
	ARIMA	RegARIMA	ARIMA	RegARIMA
N1	18.10%	20.09%	19.70%	19.99%
N2	8.90%	9.58%	10.90%	9.17%
N3	17.60%	19.77%	20.40%	16.96%
N4	9.40%	10.49%	14.60%	11.42%
N5	10.50%	10.47%	20.20%	18.29%
N6	6.70%	7.44%	21.30%	15.23%
N7	8.40%	8.74%	18.30%	13.03%
N8	8.30%	8.70%	20.90%	21.50%
N9	8.30%	8.65%	18.50%	16.17%
N10	n/a	n/a	n/a	n/a
S1	n/a	n/a	n/a	n/a
S2	22.50%	11.96%	20.60%	22.50%
S3	21.90%	18.90%	14.00%	11.90%
S4	9.30%	8.85%	23.60%	18.00%
S5	6.60%	6.66%	20.40%	16.98%
S6	10.90%	9.98%	16.20%	13.52%
S7	10.80%	11.21%	18.50%	17.65%
S8	5.50%	5.33%	9.20%	7.68%
S9	8.60%	8.90%	21.80%	22.39%
S10	16.70%	17.48%	13.00%	14.04%
Total	11.60%	11.29%	17.90%	15.91%

Predicted day	Non-snow conditions			Snow conditions		
	ARIMA	RegARIMA	Difference	ARIMA	RegARIMA	Difference
1st day	11.80%	12.20%	-0.40%	14.30%	14.86%	-0.56%
2nd day	11.90%	11.50%	0.40%	17.50%	16.47%	1.03%
3rd day	11.20%	10.20%	1.00%	21.80%	16.40%	5.40%

4.2 Estimation of the Effects of Snow Removal Operations

The effects of snow removal operations were represented as the travel time reduction afforded by such operations. The travel time reduction is the difference in predicted travel time between the case with snow removal and that without snow removal. The predicted travel time can be derived from the predicted travel speed and the link length on each link. In the present study, the effects of snow removal operations were estimated for two types of operation: the effect of a snow removal operation conducted independently, and the effect of several snow removal operations conducted in combination during a certain period in winter.

4.2.1 Effects of a Single Snow Removal Operation

The effect of a single snow removal operation is defined as the saved travel time for the day after the operation is performed. For example, when a fresh snow removal operation was performed on the night of Jan. 6, the difference in travel time between with and without the operation on Jan. 7 is defined as the fresh snow removal effect. The travel time saved by a snow removal operation is transformed into the travel time-saving benefit (Equation 4).

$$(Travel\ time\ saving\ benefit)_i = \left(\sum_{t=7}^{20} \frac{(Link\ length)_i}{(Predicted\ travel\ speed)_{it\_with}} - \sum_{t=7}^{20} \frac{(Link\ length)_i}{(Predicted\ travel\ speed)_{it\_without}}\right) \times 60 \times U_T \quad (4)$$

Where, i is the link ID and t is the time of day from 07:00 to 20:00. with and without represent with and without the snow removal operation. U_T is the unit cost of travel time for the passenger car class (45.78 JPY/min/veh) (Regional Development Bureau, 2008).

In the winter of 2013-2014, nine fresh snow removal deployments, two road widening deployments and two snow hauling deployments were conducted, and these operations were selected to estimate the snow removal effects of each operation taken independently. The dates on which snow removal operations were performed are shown in Table 6.

Table 6. Dates on Which Snow Removal Operations Were Performed

Fresh snow removal			Road widening			Snow hauling		
ID	Date	Sections	ID	Date	Sections	ID	Date	Sections
F1	Jan. 6	All	W1	Feb. 19	All	H1	Jan. 14 ~ 23	2 ~ 10
F2	Jan. 12 & 13	All	W2	Feb. 23 & 24	5 ~ 10	H2	Mar. 8 ~ 10	5 ~ 10
F3	Jan. 21	All	n/a	n/a	n/a	n/a	n/a	n/a
F4	Feb. 4	All	n/a	n/a	n/a	n/a	n/a	n/a
F5	Feb. 5	All	n/a	n/a	n/a	n/a	n/a	n/a
F6	Feb. 11	All	n/a	n/a	n/a	n/a	n/a	n/a
F7	Feb. 13	All	n/a	n/a	n/a	n/a	n/a	n/a
F8	Feb. 17	All	n/a	n/a	n/a	n/a	n/a	n/a
F9	Feb. 21	All	n/a	n/a	n/a	n/a	n/a	n/a

Table 7 shows the benefit of travel time reduction for each snow removal operation in Table 6. Most of the fresh snow removal benefit is found to be less than 100 JPY per vehicle, and the benefit of road widening is greater than that of fresh snow removal in the study area. The benefit of snow hauling was the largest of snow removal in the present study.

Table 7. Effects of Each Snow Removal Operation (JPY/veh)

Link ID	F1	F2	F3	F4	F5	F6	F7	F8	F9	W1	W2	H1	H2
N1	131.5	107.3	97.5	4.9	59.6	57.2	57.7	69.4	88.3	64.8	n/a	n/a	n/a
N2	26.9	20.7	32.2	2.6	21.8	20.9	16.3	27.2	29.3	32.4	n/a	172.3	n/a
N3	23.2	15.9	25.3	2.2	14.5	12.5	15.4	21.1	20.8	24.2	n/a	140.7	n/a
N4	29.0	26.9	27.0	2.2	23.3	16.9	17.2	23.4	30.0	20.2	n/a	142.9	n/a
N5	22.2	15.4	11.5	1.6	17.5	12.4	14.2	33.3	31.6	30.2	31.6	149.4	142.0
N6	87.6	121.9	33.3	5.0	54.7	57.8	64.6	127.6	144.7	135.8	144.7	637.4	436.2
N7	31.8	43.8	15.2	3.1	22.6	26.2	25.4	33.9	28.9	99.8	57.4	133.5	141.9
N8	119.8	1,563.6	30.0	5.6	87.4	107.6	57.1	111.9	151.6	2,998.5	280.8	243.0	298.6
N9	19.0	13.5	12.0	1.5	13.7	13.4	14.3	17.1	18.0	13.2	14.8	93.9	84.0
N10	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
S1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
S2	66.5	832.0	334.1	3.8	37.8	38.2	36.9	48.9	67.8	52.2	n/a	219.0	n/a
S3	33.3	91.4	81.1	2.5	24.9	33.1	27.0	36.6	39.0	30.7	n/a	207.3	n/a
S4	56.5	95.4	98.1	4.0	29.7	29.9	24.4	48.0	58.9	49.2	n/a	211.1	n/a
S5	38.0	103.5	89.4	3.1	23.4	25.0	23.1	39.8	68.3	47.3	68.3	590.1	332.8
S6	71.9	101.1	31.2	4.9	41.8	40.2	40.6	60.7	71.4	52.8	71.4	651.9	327.7
S7	71.6	78.4	18.7	5.0	27.7	38.8	39.9	64.0	67.7	56.1	56.7	287.9	310.4
S8	78.1	80.4	35.2	8.7	59.4	55.6	49.4	74.0	75.3	64.8	55.8	343.1	377.0
S9	47.9	101.5	16.0	3.7	22.8	31.2	26.6	30.0	54.2	52.4	54.1	449.9	202.9
S10	64.7	62.4	35.6	6.7	42.0	51.4	40.8	50.4	56.8	51.8	50.2	379.1	353.6
Average	56.6	193.1	56.8	3.9	34.7	37.1	32.8	51.0	61.3	215.4	80.5	297.2	273.4

According to the results, some benefits of link N8 were much larger than of the other links. This is because the travel speed on link N8 was relatively slower than other links on that dates. For example, the average speed of N8 on Jan. 14 (for F2) was 7.78 km/h, while the average speed of the whole study area on that date was 13.73 km/h. In other words, snow removal operations were more effective on congested roads.

4.2.2 Effects of Snow Removal Operations for a Period

The period from Feb. 13 to 20 of 2014 was selected for estimation of the effects of snow removal operations. During this period, 22 cm of snow fell in Sapporo, and two fresh snow removals and one road widening were performed (Table 6). Four scenarios were designed for estimating the effects of snow removal operations for the period. In Scenario 1, both fresh snow removal and road widening were performed. In Scenario 2 and Scenario 3, only road widening and only fresh snow removal was considered, respectively. In Scenario 4, no snow removal was performed during the period.

The difference in the predicted travel time between Scenario 4 and each other scenario is defined as the effect of snow removal for each of those scenarios. The travel time saved by snow removal for each scenario is converted into the travel time saving benefit (Equation 5).

$$\begin{aligned}(Travel\ time\ saving\ benefit)_i &= \left(\sum_{d=13}^{20}\sum_{t=7}^{20}\frac{(Link\ length)_i}{(Predicted\ travel\ speed)_{idt\_4}} \right.\\ &\quad \left. -\sum_{d=13}^{20}\sum_{t=7}^{20}\frac{(Link\ length)_i}{(Predicted\ travel\ speed)_{idt\_S}}\right)\times 60\times U_T\end{aligned} \tag{5}$$

Where, d is each date from Feb. 13 to Feb. 20. S is the scenario (1, 2, or 3).

The benefits determined for each snow removal scenario are listed in Table 8. Scenario 1 is found to save 4,392 JPY per vehicle from Scenario 4 (no snow removal) during the period. The benefits of Scenarios 2 and 3 were 1,076 and 3,420 JPY per vehicle during the period. The benefits of fresh snow removal exceed those of road widening during the period. This is because each operation has a different duration of effectiveness. Road widening was performed on the night of Feb. 19, whereas fresh snow removal was performed on the nights of Feb. 13 and 17. Although the total benefits of fresh snow removal exceed those of road widening during the period, Figure 3 shows that the difference in the predicted speeds between Scenario 4 and Scenario 2 slightly exceed the difference between Scenario 4 and Scenario 3 on Feb. 20. In other words, the benefits of snow removal in the present study were not absolute; rather, they differ according to the selected period. However, the traffic administrators can estimate the effects of snow removal operations by the suggested methodology on their selected period to perform more cost-effective snow removal operations.

Table 8. Effects of Snow Removal from Feb. 13 to Feb. 20

Link ID	(Scenario 1) Road widening + fresh snow removal		(Scenario 2) Road widening only		(Scenario 3) Fresh snow removal only	
	travel time reduction (min/veh)	benefit (JPY/veh)	travel time reduction (min/veh)	benefit (JPY/veh)	travel time reduction (min/veh)	benefit (JPY/veh)
N1	7.12	325.91	1.63	74.45	5.66	259.12
N2	2.37	108.68	0.55	25.14	1.86	84.92
N3	1.89	86.65	0.44	20.06	1.48	67.70
N4	2.31	105.65	0.53	24.11	1.81	82.99
N5	2.78	127.12	0.67	30.50	2.16	98.67
N6	15.89	727.47	4.22	193.07	12.25	560.61
N7	3.45	157.93	0.82	37.66	2.69	123.24
N8	15.86	726.18	4.23	193.68	12.15	556.30
N9	1.51	69.28	0.35	15.84	1.19	54.26
N10	n/a	n/a	n/a	n/a	n/a	n/a
S1	n/a	n/a	n/a	n/a	n/a	n/a
S2	5.13	235.07	1.23	56.29	4.00	183.35
S3	3.64	166.60	0.85	39.12	2.85	130.47
S4	3.10	142.11	0.71	32.72	2.44	111.66
S5	2.54	116.21	0.56	25.54	2.02	92.26
S6	5.18	237.31	1.20	54.98	4.07	186.37
S7	5.98	273.55	1.46	66.98	4.66	213.54
S8	6.75	309.12	1.59	72.60	5.28	241.80
S9	4.08	186.84	0.98	45.04	3.18	145.73
S10	6.33	289.94	1.50	68.45	4.96	227.05
Total	95.93	4,391.64	23.51	1,076.23	74.71	3,420.06

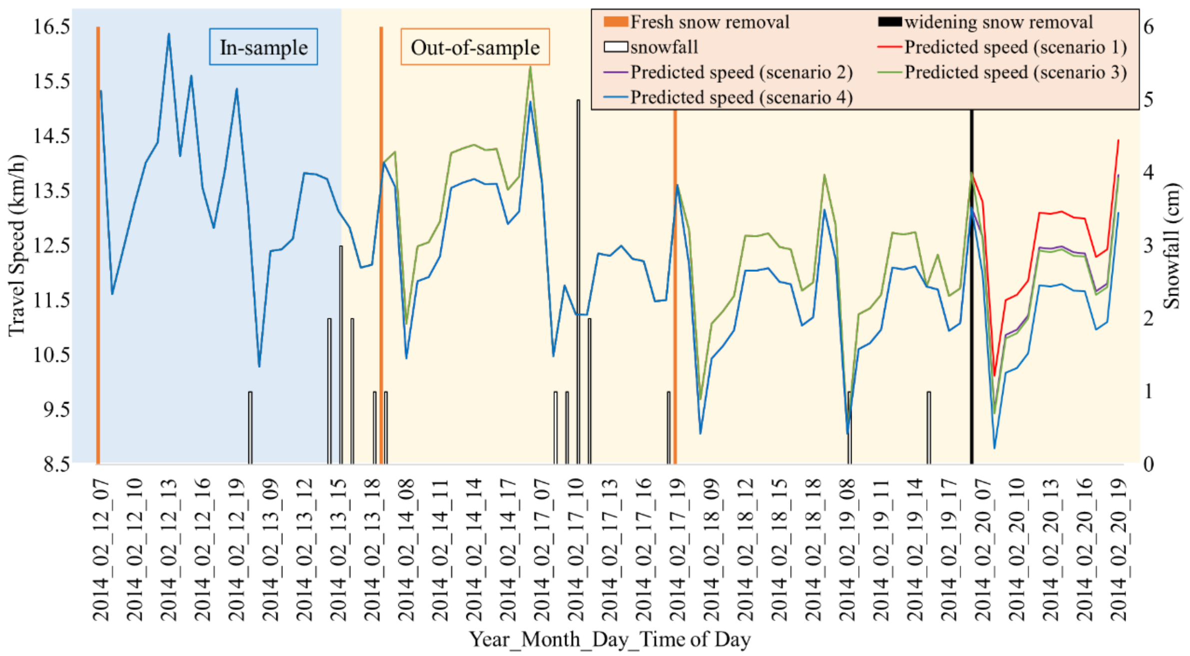

Figure 3. Predicted travel speed profiles for each snow removal scenario (Link: S7)

5. DISSCUSSION AND CONCLUSION

The effects of snow removal operations on traffic performance were rarely considered in previous studies. Therefore, the present study developed a methodology for quantifying snow removal effects by using the RegARIMA model. The study area was an urban arterial in Sapporo, and the 2013-2014 winter was selected to estimate the snow removal effects.

The temperature was found to have a U-shaped relationship with travel speed. Deep snow had a negative correlation with travel speed. Meanwhile, both snow removal operations (i.e., road widening and fresh snow removal) had a positive correlation with travel speed. The predictive accuracies of travel speed for the ARIMA and the RegARIMA under different weather conditions were compared. RegARIMA was found to be more stable over time, regardless weather.

The travel time reduction afforded by snow removal was defined as the effect of snow removal, and the travel time reduction was converted into travel time saving benefit. The effect of a single snow removal operation and the effect of several snow removal operations in combination during a week were considered. The fresh snow removal benefit was found to be less than 100 JPY per vehicle, and the effects of snow hauling were the greatest of any snow removal operation.

The suggested methodology can be used for developing winter road maintenance strategies that aim to reduce traffic congestion in winter. For example, although the current snow removal strategy in Sapporo is based on snowfall accumulation, it could be changed based on the travel speed reduction rate to improve the strategy.

Based on the results of this study, further research is needed to obtain more reliable results. First, only five independent variables were used in this study, so if additional independent variables, such as road surface conditions, traffic volume, and measured effective road width, were considered in the models, it would help toward the development of more reliable travel speed estimation models. Second, urban roads have many intersections. Therefore, not only should the impacts of winter weather and snow removal operations on a single arterial be considered, but so should those impacts on the overall road network be considered. Finally, more accurate weather data would be helpful. The weather data of the present study were collected from a weather station that is a few kilometers from the study area. However, if the road weather information system (RWIS) data were used, the results would be improved.

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