A Trafficability Index to Safely Operate Roadway Network and Vehicles during Winter

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Abstract

Information about trafficability, or the condition of a roadway section with regard to its being traveled over by vehicles, is one of the most critical factors for roadway operation in winter. Specifically, when traveling on snowy or icy surfaces, the traction varies per vehicle types, tire types, geometric characteristics of the roadway, and conditions of the roadway surfaces. Thus, traffic information regarding trafficability with respect to vehicle types, geometric characteristics of roadway sections, and roadway surface conditions can provide a foundation to make a decision whether to use the associated roadway sections for roadway operators as well as users. Based on the preceding premise, the objective of this study is to present a methodology for developing a trafficability index with respect to vehicle types, geometric characteristics of roadway sections, and roadway surface conditions. Two datasets were combined to accomplish the objective of the study: (1) traction data from previous studies, and (2) road geometry data obtained from suburban area in Seoul metropolitan area, Korea.

Keywords: Friction, Trafficability, Roadway Surface Condition, Trafficability Index, Weather Information, Information Convergence

1 INTRODUCTION

One of the most critical problems for roadway operators in the winter may be the snow removal work. Apart from the snow removal issue, roadway operators and users are commonly faced with the decision making if a specific section such an uphill section will be trafficable when the snow was forecasted. The problem regarding the decrease of trafficability mainly erupts in uphill sections rather than on plains. In other words, a snowfall on an uphill section of a roadway reduces the friction between the vehicle and the roadway thus making the uphill section impossible to climb or safely descend. In particular, few drivers would expect that they can climb the uphill section by using the power of vehicle's acceleration. However, when such trials lead to fail in roadways with a small number of lanes, there could be traffic congestion or vehicle's isolation due to hampering the entry of other vehicles and snow removal vehicles. This problem is likely due to the lack of information with respect to the trafficability of roadway sections.

In general, even if the surface conditions and the geometric characteristics of the roadway are the same, the trafficability of vehicles varies with the vehicle's performance. In other words, in spite of the same roadway conditions and the geometric characteristics, certain vehicles cannot travel the roadway section, but others can. Thus, if information regarding weather conditions or roadway conditions and the geometric characteristics of the roadway is fused, the trafficable index for the winter roadway can be built for the purpose of the roadway operation and vehicle control. Although such an index-based information is expected to be used as highly useful, none of the previous studies has been found based on the literature reviewed by the author. With this background, the objective of this study is to develop a roadway trafficability index based on information regarding the roadway geometry, vehicle characteristics, and roadway surface conditions. To accomplish this objective, this study used the existing research results on the roadway friction with respect to vehicle types.

2 LITERATURE REVIEW

2.1 Traction performance

Generally, the possibility of whether a particular vehicle can or cannot pass through the particular roadway section can be determined by the following factors:

- Roadway grade
- Vehicle's driving force
- Road surface conditions regarding the weather conditions

Physically, the force when a vehicle is on a roadway is the grade of the roadway sections, which consist of the force acting in the direction towards the ascent of the section (vehicle driving force), and the resistance force sliding towards the downhill section as shown in Figure 1 and these two forces are represented by the following formula (Raad and Lu, 1998, Raad and Lu, 2000):

- Driving force: $\mu mg\cos\theta$
- Resistance force: $mg\sin\theta$

where m represents the mass of the vehicle, g is the ground acceleration, μ is the rolling resistance coefficient, θ is the slope of roadway section.

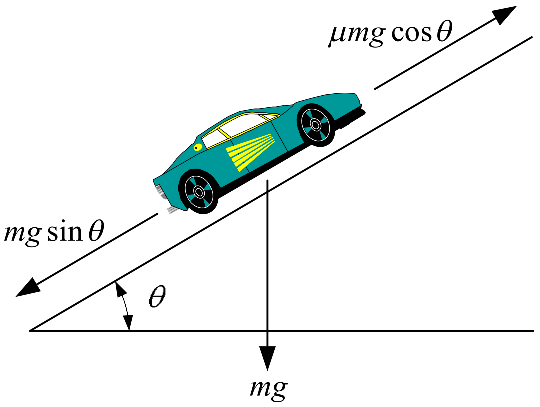

Figure 1 Forces for a vehicle at its maximum climbing ability

Thus, the maximum climbing degree of a vehicle is the point when the driving force and the resistance force are equal. This relationship can be expressed as follows:

$$\mu mg\cos\theta_{\max} = mg\sin\theta_{\max} \tag{1}$$

where $\theta_{\max}$ represents the maximum climbable degree. In this equation, the vehicle mass varies with the type of vehicles and the coefficient of the rolling resistance can be measured through experiments. Furthermore, the variable g is generally applied to the acceleration of gravity and $mg\cos\theta$ is described as the maximum static friction force. However, g is applied to the acceleration of the vehicle, since it is describing the driving state of the vehicle.

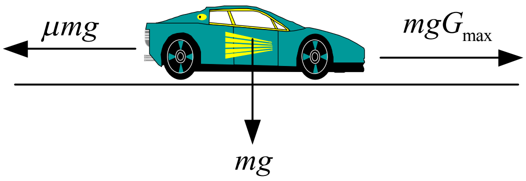

Figure 2 Forces for a vehicle on a level surface

Based on the foregoing description, the maximum trafficability of the vehicle can be derived for a particular type of vehicle on a particular roadway section condition. This situation is shown in Figure 2. That is, the maximum traction or maximum G ($G_{\max}$), defined as the average friction coefficient between the tires and the ground surface, can be derived when $\theta = 0$ (Raad and Lu, 1998, Raad and Lu, 2000). Thus, above equation (1) can be rewritten as:

$$mgG_{\max} = mg\mu \tag{2}$$

or

$$G_{\max} = \mu \tag{3}$$

In addition, by using equation (1) and (3), the following equation (4) can also be derived. As a result, once the $G_{\max}$ values for the individual vehicles and the surface conditions for each roadway section can be found, the maximum trafficable degree for individual vehicles with respect to various roadway surface conditions can be identified. Therefore, equation (4) shows that increasing the friction coefficient results in greater the trafficability degree (or climbing angle).

$$G_{\max} = \tan\left(\theta_{\max}\right) \tag{4}$$

2.2 Previous studies

Research related to the friction between the road surface and vehicle has been mostly focused on the type of tires based on the characteristics of friction. In Europe and North America, such studies were conducted from the 1960s and early 1970s (Rosenthal, Haselton, Bird and Joseph, 1969, Fromm and Corkill, 1971, Smith and Schonfeld, 1970, Smith, Ewens and Clough, 1971, Greek, 1975), and most of them were focused on measuring the stopping distance. The results from these studies showed that studded tires reduced the stopping distance on icy roads but increased the stopping distance on dry or wet roads.

From the 1980s, along with advancements in vehicle technology and performance, studies associated with the friction between vehicle and road surface included new factors. That is, driving surpport sustems such as four-wheel-drive vehicles and anti-lock braking system (ABS) were newly introdueced in experiments. Hayhoe and Kopac (1982) conducted a study on the braking friction and traction force of general tires, snow tires, studded tires, four-wheel-drive vehicles, four-wheel and ABS-equipped vehicles and rear-wheel and ABS-equipped vehicles. According to the results of their experiments, studded tires were found to have good braking performance on icy roads and both snow tires and studded tires were shown to have the same performance on snowy roads, but on wet roads all equipments had the same performance. On the other hand, in the case with traction force, four-wheel drive systems had the most excellent performance on icy and snowy roads, followed by studded tires. Other equipments were shown to have the same performance. In addition, four-wheel drive vehicles were shown to have the most remarkable performance on wet roads and other equipments had the same performance.

In the 1990s, more advanced tire technology was developed. As a result, the number one tire manufacturing company, Bridgestone, launched a new type of tire called Blizzak. The researchers at the University of Alaska in the United States performed an experiment related to vehicle traction force both on snowy and icy roads regarding three types of tires (Lu, Junge and Esch, 1994). Table 1 represents the results of their experiments.

Table 1 Example of average traction study results

Type of tires	Blizzak		Studded		All-season	
Traction test	Snow	Ice	Snow	Ice	Snow	Ice

Stopping distance (40.2km/h)	19.5	36.5	32.3	32.3	19.3	39.1
Starting traction (time in sec to reach 42.2km/h)	9.6	14.4	9.1	11.9	10.5	16.7
Maximum cornering speed (15.2m radius in km/h)	27.7	22.8	25.6	21.9	27.7	22.0
Maximum starting grade (%)	16	11	16	12	15	10

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In the late 1990s, Raad and Lu (1998) evaluated the winter traction performance of transit and paratransit vehicles including a 9-passenger van, 1 30-passenger bus, and a 35-passenger bus. In this study, stopping distance, starting traction, maximum hill-climbing ability, and degree of vehicle movement direction change occurring with sudden stops were tested with respect to both snow and icy road surfaces. Recently, vehicle traction characteristics were investigated on the more diverse road surfaces (Sokolovskij, 2007). Specifically, this study was tested by classifying the road surfaces into 12 cases rather than 2 cases (i.e., snow and icy surfaces).

As we have seen so far, the research related to the friction between the road and the vehicle or the traction has been mostly conducted to estimate the friction coefficient on simple changes in the external environment. In the field of transportation engineering, the friction coefficient is mainly used for the purpose of the accident prevention during winter due to reducing the friction between the road surface and the vehicle (Sokolovskij, 2007, Scheibe, 2002). In other words, limited studies have been accomplished to establish the operational criteria for the road networks and vehicles with respect to the geometric characteristics of the roadways, vehicle types, and weather conditions.

With this background, this study develops a basic information to make a decision whether or not a specific type of vehicles will pass a specific roadway section under the consideration of various external conditions such as the geometric condition, vehicle performance, and weather conditions during winter. The friction coefficients estimated by previous studies were used to accomplish this purpose.

3 TRAFFICABILITY INDEX

3.1 Average maximum friction coefficient of vehicles

The friction coefficient for various types of vehicles can be obtained by experiments. However, this study used the values from the maximum average friction coefficient ($G_{\max}$) suggested by Raad and Lu (2000). Specifically, the type of vehicles for the trafficability index was simplified to passenger car, vans, bus, and light truck. However, the values of other vehicles not shown in Table 2 can be estimated by using the interpolation method based on the vehicle weight.

Table 2 Examples of $G_{\max}$ by vehicle types on non-battered snow

Type of vehicles	Vehicle weight	$G_{\max}$
Passenger car	1.5t	0.14
Van	4.6t	0.15
Bus	15.4t	0.16
Light truck	1.8t	0.14

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3.2 Average maximum friction coefficient of vehicles

Traction implies to a machine's ability to continue moving forward without the wheels slipping (Burch, 2004), and it refers the maximum friction that can be produced between the road surface and vehicle without slipping. In addition, the coefficient of traction is defined as the usable force for traction divided by the weight on the vehicle. Thus, the coefficient of traction (ϕ) is a critical variable that can determine whether or not a vehicle can climb an uphill roadway section without slipping. The traction coefficient is also affected by the type of pavements and weather conditions. In this study, the pavement type of the road was assumed as asphalt and the traction coefficient for weather conditions used the results from the study by Sokolovskij (2007). Table 3 shows the traction coefficient (ϕ) of vehicles with respect to the road surface conditions by Sokolovskij.

Table 3 Traction coefficient of universal tire by road surface conditions

Road surface	More detailed description of the surface condition	Traction coefficient ϕ
Battered snow	Snow, battered by automobiles, which does not make the pounded layer of snow and ice	0.24~0.37
Non-battered snow	Snow, which has just fallen on the asphalt and which is not battered by the wheels of automobiles - the first driving	0.15~0.42
Snow and ice, covered with the snow, which has just fallen	Battered snow and ice, covered with the layer of snow (thickness − up to 10 cm), which has just fallen and is not battered	0.18~0.45
Snow and ice, mixed with sand and slush	Battered snow and ice, mixed with sand and slush, the particles of which make 3–6 mm in diameter	Depending upon the quantity of slush (little − much) 0.15~0.45
Snow and ice	Entire layer of snow, battered to the extent of the icy surface	0.12~0.39
Snow and ice before crossroads	Snow, which at first was melted by the motors of the standing automobiles and then frozen up to the smooth surface	0.09~0.22
Dry asphalt in winter conditions	Dry asphalt (not covered by anything) in winter conditions	0.59~0.72
Asphalt, covered with hoar-frost	White cover on the asphalt, which is observed by the driver and easily recognized as hoar-frost	0.48~0.58
Smooth ice	Thick layer of frozen water, non-infringed with prickles and chains	0.054~0.19
Ice and tires with chains	Thick non-infringed layer of frozen water, infringed with the wheels, equipped with steel chains	0.12~0.18
Black ice	Thick ice layer, looking as a wet, black stretch of the road, which seems fit for traffic, and is not easily noticed by the driver	0.12~0.26

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3.3 Trafficable slope

The values proposed in Table 2 refer to the average maximum friction coefficients ($G_{\max}$) of vehicles on non-battered snow. The $G_{\max}$ values for passenger vehicles appeared to be 0.14. On the other hand, the values presented in Table 3 displays the traction coefficients (ϕ) of universal tires with respect to the road surface conditions. As described by Sokolovskij (2007), the range of the traction coefficient for the case of non-battered snow in Table 3 is comparatively wide (i.e., 0.15~0.42) according to the experimental conditions, tire conditions, weather conditions, and other variables. Although the spatio-temporally experimental environment to obtain the result of Table 2 and Table 3 was different, the $G_{\max}$ value is very similar to the lowest value of ϕ. As described above, therefore, the average maximum friction coefficient can be referred as the traction coefficient.

However, the use of conservative values in the rage of the ϕ value is recommended in the perspective of safe traffic operation and control strategies. Thus, this study applies the lowest value in the rage values. Based on this idea, the average maximum friction coefficient $G_{\max(i,j)}$ for the road surface condition i and for the vehicle type j can be calculated by using the $G_{\max}$ value in Table 2 and the ϕ value in Table 3. Table 4 represents the calculated $G_{\max(i,j)}$, and Table 5 shows the degree of maximum slope with respect to vehicle types and road surface conditions, which is obtained by using the unit conversion to degree (°) and equation (4).

Table 4 Summary of $G_{\max(i,j)}$ for vehicle types and road surface conditions

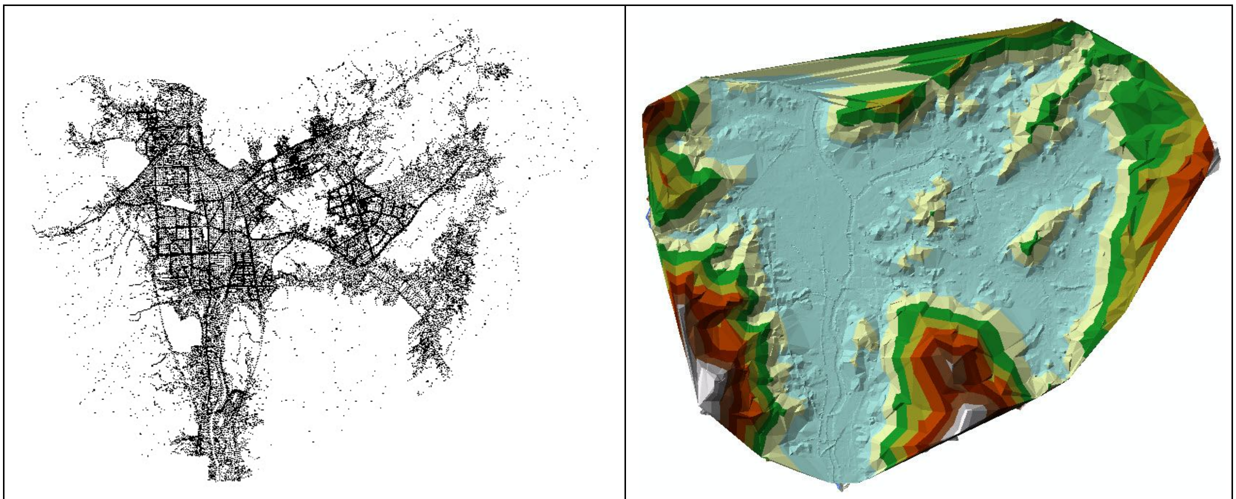
Road surface condition i	$G_{\max(i,j)}$ for vehicle type j			
	Passenger car	Van	Bus	Light truck
Battered snow	0.24	0.257	0.274	0.24
Non-battered snow	0.15	0.161	0.171	0.15
Snow and ice, covered with the snow, which has just fallen	0.18	0.193	0.206	0.18
Snow and ice, mixed with sand and slush	0.15	0.161	0.171	0.15
Snow and ice	0.12	0.129	0.137	0.12
Snow and ice before crossroads	0.09	0.096	0.103	0.09
Dry asphalt in winter conditions	0.59	0.632	0.674	0.59
Asphalt, covered with hoar-frost	0.48	0.514	0.549	0.48
Smooth ice	0.054	0.058	0.062	0.054
Ice and tires with chains	0.12	0.129	0.137	0.12
Black ice	0.12	0.129	0.137	0.12

Table 5 Degree of maximum slope for vehicle types and road surface conditions

Road surface condition i	Maximum slope for vehicle type j in degree			
	Passenger car	Van	Bus	Light truck
Battered snow	13.50	14.42	15.34	13.50
Non-battered snow	8.53	9.13	9.73	8.53
Snow and ice, covered with the snow, which has just fallen	10.20	10.92	11.62	10.20
Snow and ice, mixed with sand and slush	8.53	9.13	9.73	8.53
Snow and ice	6.84	7.33	7.81	6.84
Snow and ice before crossroads	5.14	5.51	5.87	5.14
Dry asphalt in winter conditions	30.54	32.30	33.99	30.54
Asphalt, covered with hoar-frost	25.64	27.22	28.75	25.64
Smooth ice	3.09	3.31	3.53	3.09
Ice and tires with chains	6.84	7.33	7.81	6.84
Black ice	6.84	7.33	7.81	6.84

3.4 Slope of roadway segment

The slope of the roadway segment in the suburban area of Seoul metropolitan area, Korea has been estimated by using a geographic information systems (GIS) modeling with the ArcMap software by ESRI (Environmental Systems Research Institute). To estimate the slope value, two data files were used: CAD (computer-aided design) drawing file for the principal facilities of cities and digital roadway map file. In general, the digital roadway map does not include the elevation data of the roadway, but the CAD drawing file has. Thus, the first step was to capture the principal elevation spots of the city area from the CAD file scaled in 1:1000. The 3D Analyst tools of the ArcMap enables to create the triangulated irregular network (TIN) from the captured elevation spots. Figure 3 shows the created TIN based on the elevation spots of a city.

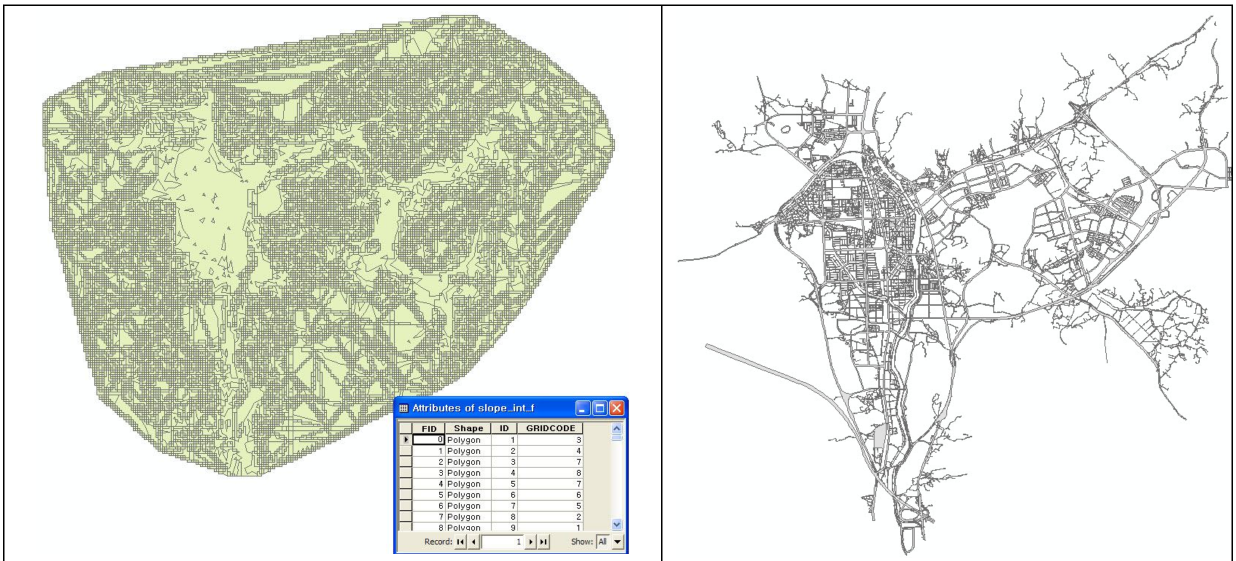


(a) Principal elevation spots of a city area

(a) TIN created by principal elevation spots

Figure 3 CAD drawing data and TIN based on principal elevation spots of a city

The TIN data is applied to construct topographical features on the slope by using the 3D Analyst tools and the Spatial Analyst Tools. Figure 4 (a) depicts the shape file including slope information. The last step is clipping the roadway map in Figure 4 (b) from the topographical features on the slope in Figure 4 (a). Finally, Figure 5 represents the roadway slope map with small segments clipped by the topographical features.



FID	Shape	ID	GRIDCODE
0	Polygon	1	3
1	Polygon	2	4
2	Polygon	3	7
3	Polygon	4	8
4	Polygon	5	7
5	Polygon	6	6
6	Polygon	7	5
7	Polygon	8	2
8	Polygon	9	1

(a) Converted topographical features on the slope

(b) Roadway map

Figure 4 Topographical features on the slope and roadway network of a city area

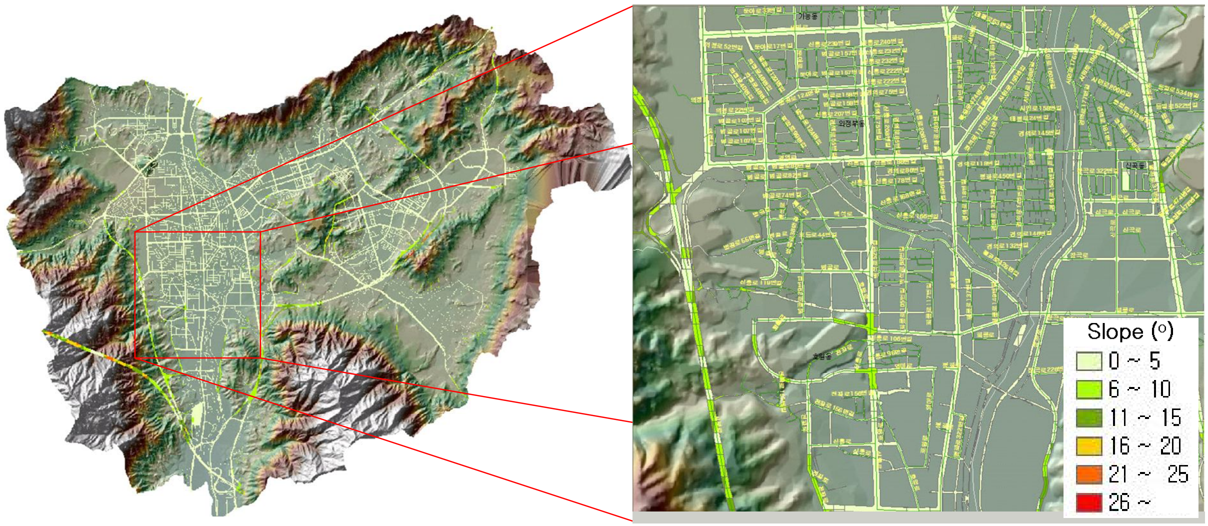


Figure 5 Roadway slope map with small segments

3.5 Trafficability index

By comparing the trafficable slope for the vehicle types and the road surface conditions with the slope of the roadway segment, the trafficability of each vehicle can also be determined. If such information is delivered to drivers as traffic information in real time or in advance based on weather forecasts, drivers can make a decision on the basis of a binary case (i.e., possible or impossible). Therefore, the development of a 'trafficability index', which includes the concept of the probability for decision making, is required.

The Trafficability Index (TI_{ijk}) of the road surface conditions i of vehicles j on road segments k can be obtained based on the $G_{\max}$ as follows:

$$TI_{ijk} = 1 - \frac{\tan(\theta_k)}{G_{\max(i,j)}} \tag{5}$$

where $G_{\max(i,j)}$ represents the average maximum friction coefficient of vehicle type j on road surface conditions i and θ_k represents the slope of road segments k in degree (°). Thus, in the case that the value of the trafficability index of vehicle type j on the road surface conditions i is $TI_{ijk} \leq 0$, it implies that the travel of the associated vehicle on the road segment k is impossible, and in the case with $0 < TI_{ijk} < 1$, the travel is probabilistically possible, and finally in the case with $TI_{ijk} = 1$, the travel is possible. In other words, as the TI_{ijk} value is closer to 1, the vehicle's travel is more possible and in the case with TI_{ijk} being smaller than 0, the possibility of trafficability is zero. Furthermore, TI_{ijk} being 1 means that θ_k is 0, meaning that there is no inclined angle, so any travel is expected to be possible in the current condition. Finally, in the case that the value of TI_{ijk} is between 0 and 1, the Road Administration or the road management officials can determine whether or not the vehicle can pass.

4 CONCLUSIONS

This paper presented a procedure to develop a trafficability index as a countermeasure of the safe driving and safe traffic operation in winter. Although the developed index used the results from the previous studies, the presented parameter values can be constructed through the field test and the presented procedures. The developed trafficability index will be useful to determine whether or not the Road Administration and the road management officials close the associated roadway section when snowfall event occurs. Furthermore, if such an index is delivered to drivers as traffic information, they will be able to detour their initially planned route or prepare special equipment such as chains and snow tires in advance. As a result, the traffic accidents and congestion due to roadway slippery will be reduced.

The trafficability index during the winter season may be constructed in real time on the basis of the information regarding current road surface and weather conditions and the vehicle types. However, since weather information is a kind of predictable one, the trafficability index can also be predictable based on the predicted weather information. Thus, the trafficability index can be developed on the nationwide road networks, and it is expected to be used by drivers who are planning winter vacations. Furthermore, for the case of the logistics industries, their transportation damage due to heavy snowfall is expected to be minimized by evading snowfall-expected sections where travel is impossible and by modifying their travel schedule. Finally, this study focused on the trafficability in uphill sections, but the study related to the diagnosis on the issues associated with the loss in braking ability in downhill sections is required as future research. Also, an in-depth study of the trafficability that may vary with the braking ability and performance of a vehicle is required and this detailed research is expected to be conducted focusing on mid-to-large-size trucks which degrade the uphill trafficability.

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