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CHARACTERIZING URBAN NETWORK PERFORMANCE USING TWO-FLUID MODEL

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Abstract: This paper presents the two applications of the two-fluid model: characterizing the network performance of a subnetwork in Seoul ("Seoul Kangnam network"), and analyzing the snowing impact on the network wide performance. More than ten thousand probe data each day were collected and analyzed. The data contains moving and stopping times with their positions. According to the comparison with other cities in literature, the Seoul Kangnam network has lower parameter n (about 0.90) and higher parameter T_m (about 2.17) in normal traffic condition. Therefore, the Seoul Kangnam network turned out to need operational improvement during off-peak period but to keep sustainable network performance during peak period. The prominent parameter change was observed. About three days were needed to recover the normal network performance after snowing in the example cases. This paper shows the potential usefulness of the two-fluid model in quickly evaluating various network wide impact including snowing, raining, construction etc.

Key words: (two-fluid model, macroscopic evaluation, probe vehicle)

1. INTRODUCTION

Researchers have been interested in macroscopically characterizing urban transportation network with various traffic operation components including signalized intersections and curbside activities. Among many, average travel speed, stop time per unit distance, variation of acceleration, and fuel consumption were deeply investigated (Chang and Herman, 1978; Herman et al, 1978). However, few results can be used in general urban networks. Two-fluid model which was suggested by Herman and Prigogine(1979) is predominant in evaluating the urban transportation network with sound theoretical base in this arena.

When the concentration rises so that the traffic is in the collective flow regime, the flow pattern becomes largely independent of the will of individual drivers. Vehicle in the traffic stream are divided into two classes: moving and stopped vehicles. Those in the stopped vehicle class include vehicles stopped in the traffic stream, for example, stopped for traffic signals and stop signs, stopped for vehicles loading and unloading which are blocking a moving lane, stopped for normal congestion. The two-fluid model provides a macroscopic measure of the quality of traffic service in an urban traffic network, which is independent of concentration.

The analysis using two-fluid model needs individual probe vehicle data during analysis period such as total travel time(or distance), stop and running time(or distance) per unit distance or unit time. Therefore it is very difficult to collect basic input data for two-fluid analysis on practical application. This paper presents the two applications of the two-fluid model: the application of the two-fluid model to characterize the network performance of a sub-network in Seoul ("Seoul Kangnam network"), and the snowing impact analysis on the network wide performance. Specially, the second is the first attempt to investigate if the two-fluid model can be used for weather impact analysis.

2. TWO-FLUID THEORY

Monograph on Traffic Flow Theory(Williams et. al, 1997) presents general descriptions of two-fluid theory and introduces application cases of two-fluid theory in urban network evaluation macroscopically. The two-fluid theory of urban traffic was proposed by Herman and Prigogine(Herman and Prigogine 1979; Herman and Ardekani 1984) as a description of traffic in the collective flow regime in an urban street network. Vehicles in the traffic stream are divided into two classes: moving and stopped vehicles. The two-fluid model provides a macroscopic measure of the quality of traffic service in a street network, which is independent of concentration. Equation (1) showed the relationship between variables.

$$\ln T_r = \frac{1}{n+1}\ln T_m + \frac{n}{n+1}\ln T \tag{1}$$

Where,
T : total travel time
T_r : running time
T_m : average minimum trip time per unit distance
n : indicator of the quality of traffic service in the network

The parameter T_m is the average minimum trip time per unit distance and it represents the trip time that might be experienced by an individual vehicle alone in the network with no stops. T_m is a measure of the uncongested speed, and a higher value would indicate a lower speed, typically resulting in poorer operation. A stop time per unit distance(T_s) increases for a single value of n, the total trip time also increases. If $n = 0$, T_r is constant, and trip time would increase at the same rate as the stop time. If $n > 0$, trip time increases at a faster rate than the stop time, meaning that running time is also increasing. In other words, n is a measure of the resistance of the network to degraded operation with increasing demand. Higher values of n indicate networks that degrade faster as demand increases.

3. METHODOLOGY

Figure 1 shows the study area, Seoul Kangnam network which is severely crowded area, and Figure 2 shows the analysis process using two-fluid model.

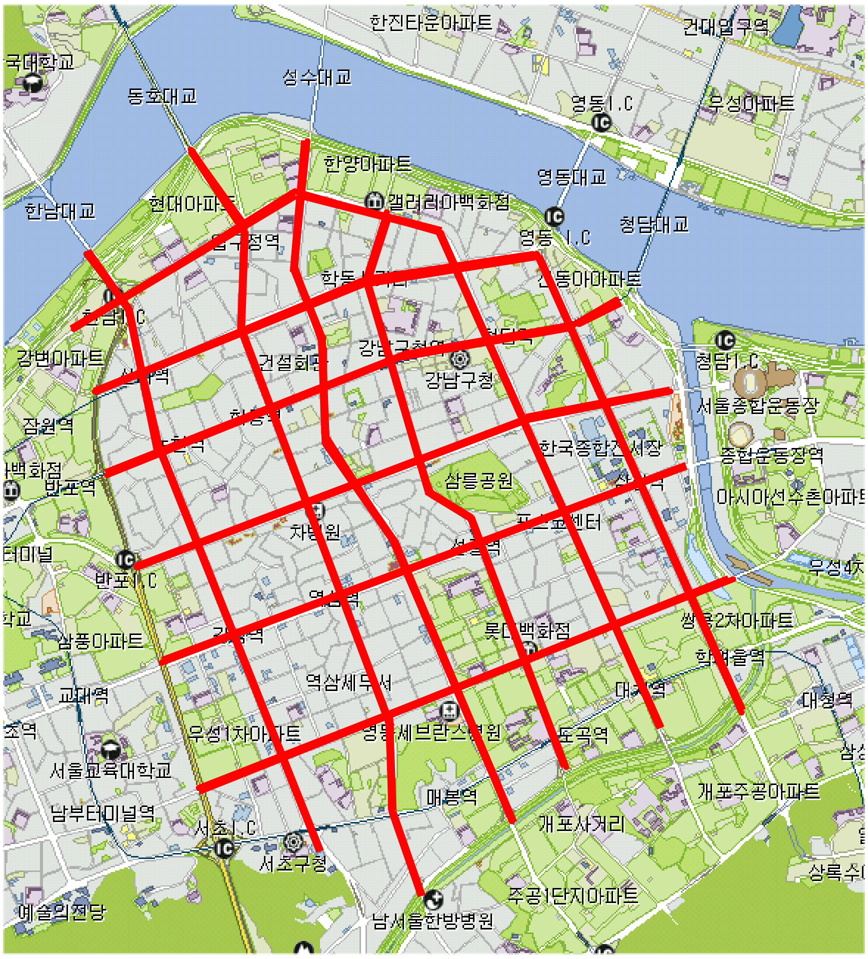

Figure 1. Seoul Kangnam Network.

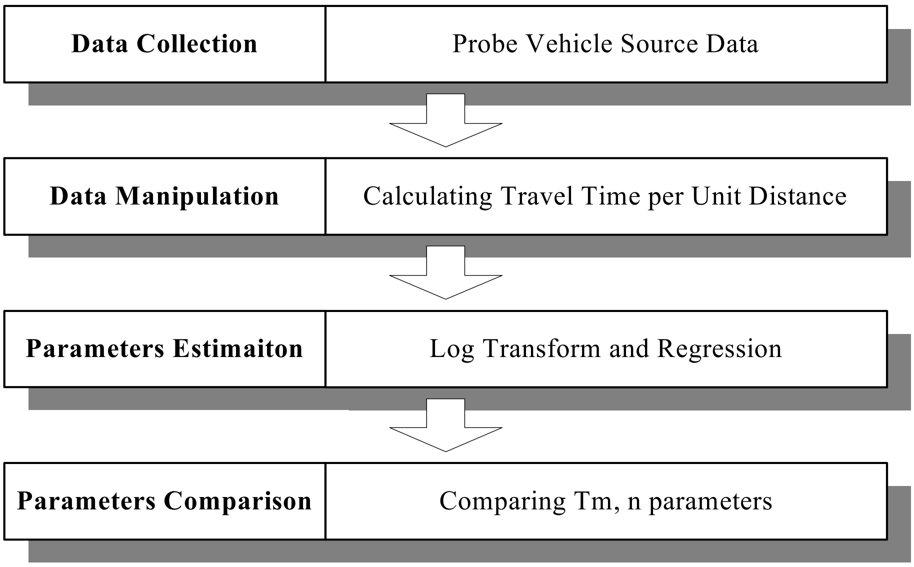

Figure 2. Analysis Process

- **Data Collection**: The probe vehicle method is generally used to collect data of two-fluid application. The ROTIS Ltd. is a private company providing various traffic information by probe vehicle operation in Seoul Metropolitan area. Among the other types of probes, only passenger vehicle probe data of the ROTIS Ltd. are used for this study. The probe data has been filtered by removing exceptional data before the parameter estimation. The data consist of vehicle ID, start node, end node, link number, entering and exit time, moving distance, moving time and stop time.
- **Data Manipulation**: Link travel time(T) and stop time(T_s) are calculated in accordance with unit distance(500 meters).
- **Parameters Estimation**: T and T_s are transformed to the logarithm of T and T_s, and two-fluid parameters, T_m and n, are estimated using linear regression method.
- **Parameters Comparison**: Finally the obtained parameters are investigated and compared with other cases.

4. RESULTS

4.1 Seoul Kangnam Network

Because traffic situation varies hourly, network performance varies in a day. This study analyzed average travel time(T), stop time(T_s) and two-fluid parameters of Seoul Kangnam network as shown in Figure 1 in three periods: 07:30~08:30, 15:00~16:00 and 18:30~19:30. Probe vehicle data were collected during Oct. 15~19 weekdays and Table 1 shows the results.

Table 1. Two-Fluid Model Analysis Results of Seoul Kangnam Network

Time	Period 1 (07:30~08:30)	Period 2 (15:00~16:00)	Period 3 (18:30~19:30)
Sample Size	9,544	9,319	8,657
$\overline{T}$ (min/500m)	1.5	2.19	2.48
$\overline{T}_s$ (min/500m)	0.59	1.00	1.18
$\overline{T}_s / \overline{T}$	0.39	0.46	0.48
T_m (min/500m)	0.658	0.697	0.702
n	0.718	0.976	1.058
R^2	0.62	0.72	0.75

The two parameters of period 2 and 3 are larger than those of period 1(Table 1). This means that the afternoon network performance is lower than that of morning. Higher curbside activities such as parking, loading and/or unloading in the afternoon may cause this result.

The parameters of Seoul Kangnam network were compared with major cities in the world: Austin, Dallas, Houston, San Antonio, Milwaukee, Brussel, London, Melbourne, Sydney etc.(Herman and Ardekani, 1984). The major cities' two-fluid parameters were reported before 1984. The recent result could not be found in literature.

Table 2. Two-Fluid Model Parameters in Literature

City	T_m (min/mile)	n	R^2
Austin	1.78	1.65	0.78
Dallas	1.97	1.48	0.80
Houston	2.70	0.80	0.63
San Antonio	2.01	1.49	0.84
Milwaukee	1.59	1.41	0.81
London	1.93	3.02	0.97
Melbourne	1.74	1.41	0.95
Sydney	1.85	1.68	0.88
Brussels	1.26	2.76	0.92
Seoul Kangnam	2.17	0.90	0.69

Figure 3 shows parameter T_m and n of various cities and Figure 4 shows the T and T_s relationship of cities.

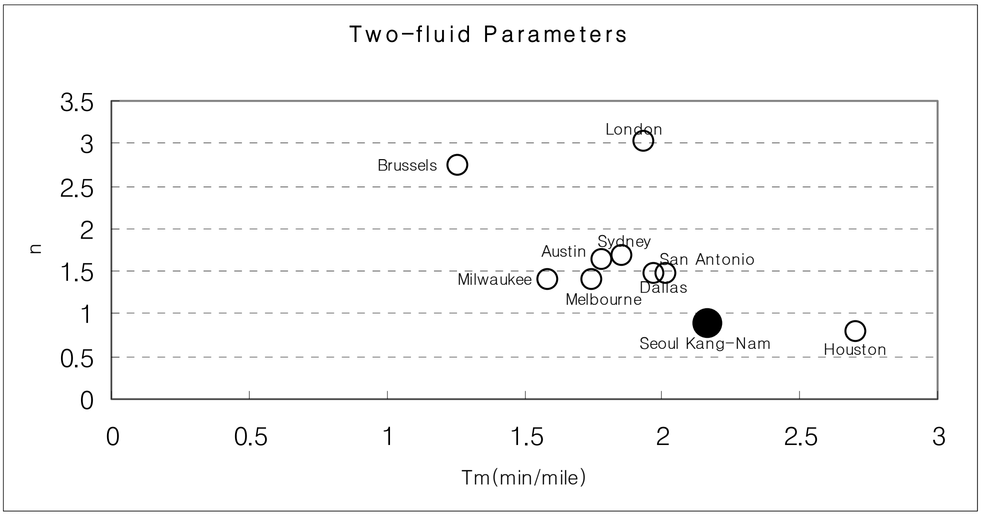

Figure 3. Two Parameters of Many Major Cities

The parameter n is a measure of the resistance of the network to degraded operation with increased demand. Higher n indicates that networks degrade faster as demand increases. The parameter T_m represents the average trip time that might be experienced by an individual vehicle along the network during off-peak. Therefore, the Seoul Kangnam network turned out to need operational improvement during off-peak period but to keep sustainable network performance during peak period.

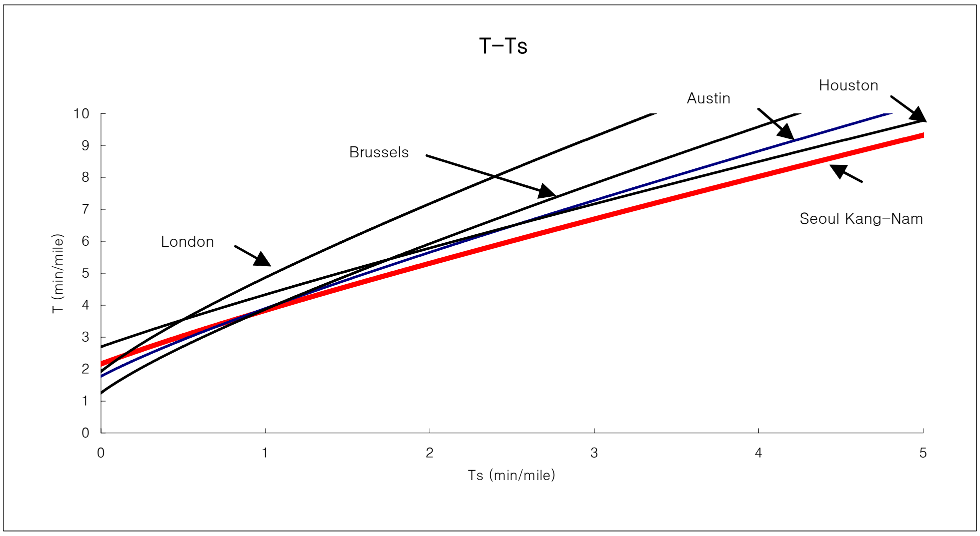

Figure 4. Relationship of T and Ts

The intercept of the Seoul Kangnam curve in Figure 4 is little higher than those of other cities. However the increasing rate of T to T_s is lower than other cities as congestion increase. This means that the Seoul Kangnam network might be relatively better in traffic operation. If the average travel time of the network is larger than the other cities, this can be explained as high demand rather than worse traffic operation might be the main reason.

$$\frac{dT}{dT_s} = \left(1 - \frac{n}{n+1}\left(\frac{T_m}{T}\right)^{1/(n+1)}\right)^{-1} \tag{2}$$

The slope of $T - T_s$ graph is affected by average travel time(T). In Herman and Ardekani(1984), London is 3.06, Milwaukee is 3.137, Brussels is 2.4 and Seoul Kangnam is 1.66 at about 20(mile/h) average speed and $T = 3$ (min/mile). Again, this means that Seoul Kangnam network relatively perform well as congestion increases.

4.2 Snowing Impact

It is obvious that snowing has big impacts on urban traffic network. But there is no example to evaluate quantitatively and macroscopically. This study performs the evaluation of snowing impact on traffic network by tracing parameter value change after snowing. In two different weather situations, i.e., normal and snowing, the probe vehicle data were collected and used to estimate the two parameters of the model. Table 3 shows the weather conditions of the analysis period. There was 23.2 mm snowing on Feb. 15, 2001. The temperature after snowing showed below or around 0℃ continually.

Table 3. Weather Data

Date	Weather	Temperature(℃)	Snowing(㎜)
Feb. 13, 2001	Clear	-6.4	-
Feb. 14, 2001	Clear	-6.4	-
Feb. 15, 2001	Snow	-5.2	23.2
Feb. 16, 2001	Clear	-8.6	-
Feb. 17, 2001	Cloudy	-7.0	-
Feb. 18, 2001	Cloudy	-0.5	-
Feb. 19, 2001	Clear	1.3	-
Feb. 20, 2001	Clear	-0.7	-
Feb. 22, 2001	Clear	1.7	-

* data collection time: 6:00 a.m. ~ 10:00 p.m.

Table 4 shows two-fluid parameters during the analysis period. The values severely increased on the snowing date, Feb. 15 and the following date, Feb 16. Because of the below 0℃ temperature, the snow did not melt down quickly, which may incur the adverse impact on the network flow. It is observed that the parameter values became to reduce and finally returned to the normal.

Table 4. Snowing Impact (Two-Fluid Model Parameters)

Date	Sample Size	T_m (min/mile)	n	R^2	SSE
Feb. 13, 2001	59,412	2.16	0.926	0.72	-
Feb. 14, 2001	54,798	2.16	0.952	0.74	-
Feb. 15, 2001	22,814	2.41	1.647	0.74	906.8
Feb. 16, 2001	37,760	3.28	1.184	0.73	-
Feb. 17, 2001	42,287	2.76	1.124	0.74	-
Feb. 18, 2001	43,058	2.31	0.875	0.63	-
Feb. 19, 2001	50,613	2.29	1.016	0.71	-
Feb. 20, 2001	56,987	2.23	1.029	0.72	-
Feb. 22, 2001	57,043	2.18	0.931	0.71	1729.6
Restricted	79,857	2.20	1.207	0.70	3047

Statistical test was conducted to identify the snowing impact with this case. In estimating two-fluid parameters, intercept(α) and slope(β) of regression function should be calculated. The structure change of regression function is tested by unrestricted model and restricted model using data manipulation. It is called "test of structural change".

$$Y_1 = \alpha_1 + \beta_1 X_1 + \mu \tag{3}$$

$$Y_2 = \alpha_2 + \beta_2 X_2 + \mu \tag{4}$$

$$Y = \alpha + \beta X + \mu \tag{5}$$

Where,

Y_1 : dependent variable of regression function on normal day

Y_2 : dependent variable of regression function on snowing day

Y : dependent variable of regression function on all days

X_1 : independent variable of regression function on normal day

X_2 : independent variable of regression function on snowing day

X : independent variable of regression function on all days

Y_1 and Y_2 are unrestricted models and Y is a restricted model. The hypothetical test is as follows:

- Null hypothesis(H_0) : $\begin{pmatrix}\alpha_1\\ \beta_1\end{pmatrix}=\begin{pmatrix}\alpha_2\\ \beta_2\end{pmatrix}$

- Test statistic : $F_{Cal}=\dfrac{(e_*^2-e^2)/q}{e^2/(n-k)}$

Where,
e_*^2 : SSE of restricted model
e^2 : SSE of unrestricted model
q : number of restriction in H_0
n : number of samples
k : number of unrestricted model parameters

If the calculated statistic(F_{Cal}) is located in critical region with α % level of significant, the null hypothesis is rejected. Therefore unrestricted model is appropriate statistically. This means that snowing obviously impacts on network performance. Table 5 shows the result of the statistical test. According to the statistical test of the structural change, the snowing incurred considerable adverse change of the parameters.

Table 5. Statistical Test

Null Hypothesis (H_0)	$\begin{pmatrix}\alpha_1\\ \beta_1\end{pmatrix}=\begin{pmatrix}\alpha_2\\ \beta_2\end{pmatrix}$
Level of Significance (α)	0.01
Critical Region, $F_{0.01}(2,\infty)$	4.61
Test Statistic, F_{Cal}	F_{Cal} = 6218.3
Decision	H_0 rejected

With additional before and after data set of the snowing, the parameter recovering trend to normal values was observed as seen in Figure 5 and 6. The trend indicates it needs about three days to recover the normal network performance after snowing in our case.

Although it needs to be further investigated with richer data in future, this paper has two important contributions: the first study to estimate the two-fluid model parameters in Korea, and the first study to apply the two –fluid model to characterize the snowing impact on the network performance. The case study opens the application possibility of real-time network performance monitoring through the parameter value observation.

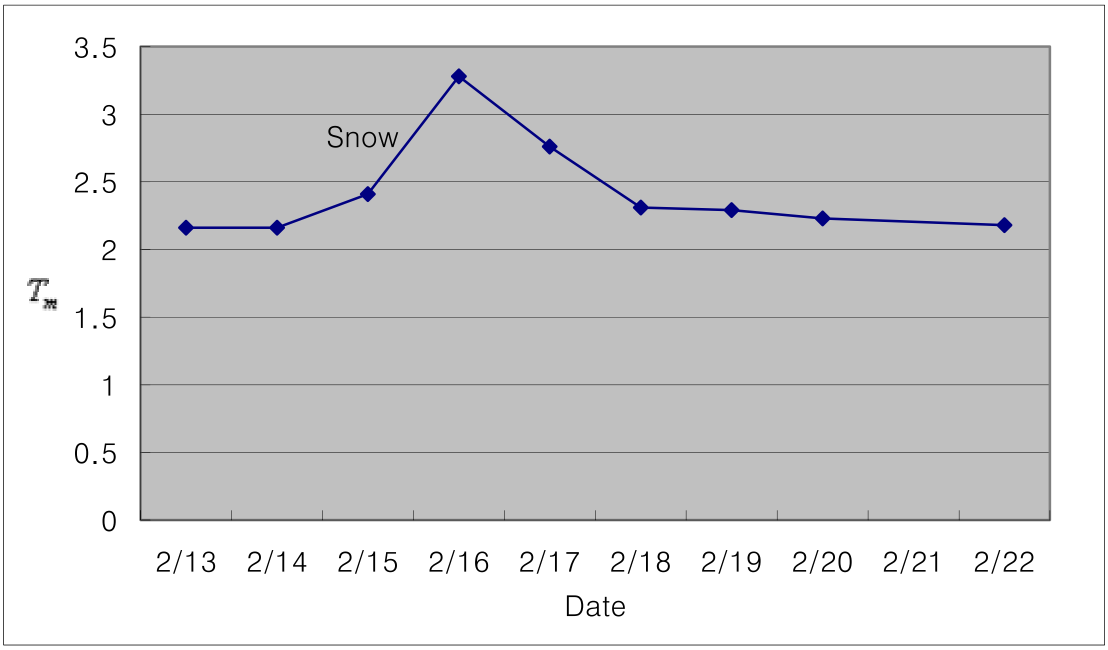

Figure 5. Trend of T_m in Seoul Kangnam

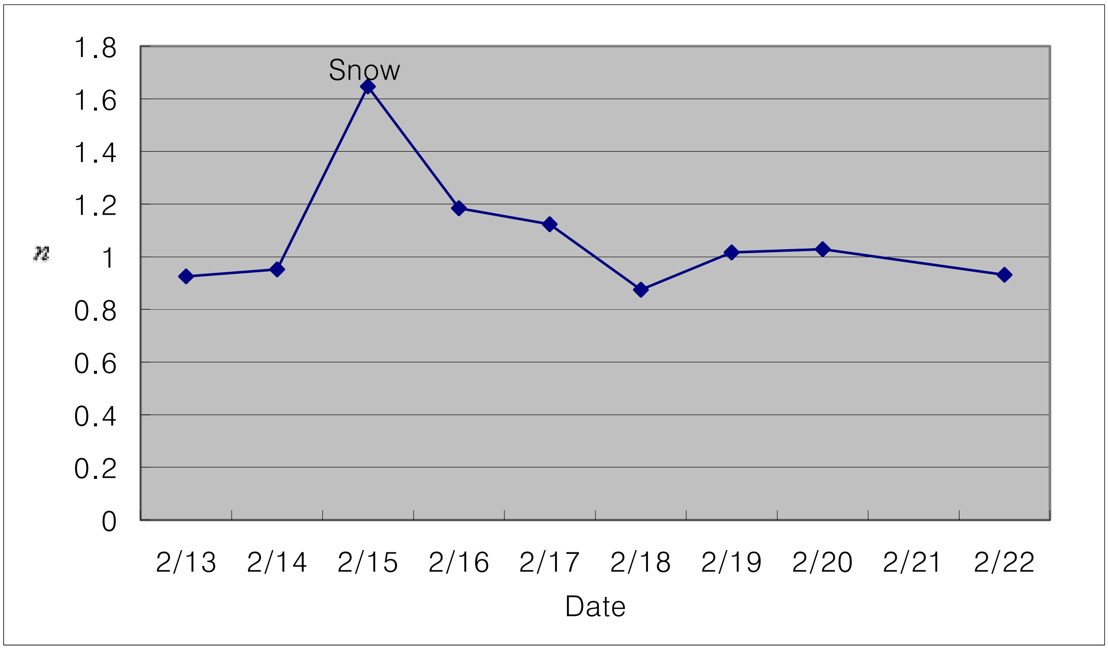

Figure 6. Trend of n in Seoul Kangnam

5. CONCLUSION

This study conducted network performance evaluation using two-fluid model, which requires massive individual vehicle data. This data collection difficulty has restricted the wide application of the model. Since the active ITS deployment, the difficulty becomes less in many cities. In a sub-network in Seoul Metropolitan, two fluid model parameters were estimated and compared with other cities' parameters reported in the literature. In the case study, afternoon network performance was relatively worse than morning, which means that the traffic operation improvement should focus on afternoon in the case network. Weather condition such as snowing may impact on the network performance. Two-fluid model was used if snowing forces the parameter values to change. Statistical test showed the parameters were different before and after snowing. Also, normal parameter value recovering trend was observed.

This study is the first trial to utilize the two-fluid model to investigate urban network flow performance change in a day-to-day base. Furthermore, the study opened the potential application possibility of the two-fluid model in a real-time fashion. Specially, the increase of probe vehicles in urban areas will overcome the data collection difficulties in the macroscopic characterizing urban networks. Ever improving telecommunication power makes it possible to easily collect individual vehicles' operational data as well. Before the real time large scale application, the richer off-line data need to be analyzed in near future.

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