CAR-FOLLOWING ANALYSIS USING DGPS DATA BASED ON GM1 MODEL

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ABSTRACT

In this paper, a car-following analysis has been conducted using Differential Global Positioning System (DGPS) to obtain data from probe vehicles on a multilane motorway in Korea. Previously, car-following researches had been performed by General Motors (GM), and certain parameters were determined by the researchers for GM1 model. In this research, these GM1 model parameters are estimated for a Korean multilane motorway. Subsequently, the GM1 model parameters estimated in this study are compared with those from certain existing studies. Sensitivity (α) is considerably higher than that in the existing ones and the reaction time (T) is similar. The parameters were estimated from limited car-following data, but, nevertheless, the results are important since they represent the first such estimation using DGPS data for a real Korean motorway.

INTRODUCTION

Car-following theory was developed from experimental studies to analyze and understand the aspect of one car following another in a single lane of traffic flow. The basic concept underlying car-following theory is the assumption that the actions of a car on the road are governed by the actions of the car immediately ahead. In other words, the actions of the leading vehicle influence flow components such as space headway, speed, and acceleration of the vehicle following it. Furthermore, these elements affect the response characteristics, or, sensitivity of the driver in the following vehicle [1].

The development and sophistication of car-following theory to describe vehicle-to-vehicle interactions has been evolved over the past several decades. Car-following theory has been most widely applied to microscopic traffic simulation programs. One of the widely used traffic simulation software package, CORSIM exploits several complex car-following equations to describe vehicle movement on a second-by-second basis [2]. By analyzing these movements, the software is able to estimate traffic flow performance characteristics such as delay, travel speed, travel time, fuel consumption, and exhaust emission. It was the General

Motors (GM) researchers who conducted extensive studies on car-following behaviors. GM researchers used parameters such as position, speed, and acceleration of two consecutive vehicles in a single traffic lane to observe behaviors of following vehicles. These parameters were collected using cars with cables and reels on the test track in GM facility.
In this research, data obtained from applying Differential Global Positioning System (DGPS) to probe vehicles in an uninterrupted facility in Korea is used to estimate GM1 model parameters. Compared to the cables and reels that GM researchers used, DGPS is a more advanced tool to collect car-following data and makes it easier to analyze the collected data since its data format can be easily converted to a computer file.

CASE STUDY

The earliest research into car-following behavior analysis was started in the 1950s. The pioneering study focused on the concept that vehicle separation was governed by safety considerations in which headway was proportional to speed [3]. Subsequently, many researchers tried to develop more sophisticated mathematical equations that incorporated distance headway, speed difference, and driver's sensitivity factor into the existing equations. As a result, GM researchers developed a generalized model (see Eq. 1). GM researches are highly regarded due to comprehensive use of field experiment data which was collected on the GM test track and within tunnels in New York [1].

$$\mathrm{response} = \mathrm{Func}(\mathrm{sensitivity}, \mathrm{stimuli}) \tag{1}$$

In the GM studies, a car-following behavior is assumed to be a stimulus-response mechanism. In the relationship given by Eq. 1, the stimulus is the speed difference between the leading and following vehicles, the response is presented as the acceleration or deceleration of the following vehicles, and the sensitivity describes the different levels of response observed for different drivers under various distance headway and speed conditions [4]. The GM model increased in complexity when it used to describe and estimate the sensitivity and time lag factors of the model. The process produced four special forms of equations and a single general case equation known as the GM fifth model [4]. The fifth model given by Eq. 2, is a general case of the GM car-following equations in which a distance headway exponent *l* and a speed exponent *m* are used to specify each specific model [5].

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_{l,m}[\dot{x}_{n+1}(t+T)]^m}{[x_n(t) - x_{n+1}(t)]^l}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{2}$$

Here, $x_n(t)$ is the distance of the leading vehicle from the starting point at time t; $x_{n+1}(t)$, the distance of the following vehicle from the starting point at time t; $\dot{x}_n(t)$, the speed of the leading vehicle at time t; $\dot{x}_{n+1}(t)$, the speed of the following vehicle at time t; $\ddot{x}_{n+1}(t+\Delta t)$, the acceleration of the following vehicle at time t+Δt; Δt, the response time for the driver in the following vehicle; *l*, *m,* the exponents of the distance headway and the speed of the following vehicle; and α, a sensitivity parameter [1].

The four specific cases of the GM car-following equations model the stimulus/response mechanism in different and more complicated methods. Each of these equations could be derived from the fifth model by using various values of *m* and *l* components.

In the first and second models, where *m* and *l* = 0, the numerator and denominator reduced to a value of 1. In this manner, they express a linear relationship between response (acceleration or deceleration) and speed difference between the leading and following cars. The first and second GM models are shown in (3) and (4) [1]. The main difference between the first and second models lies in the sensitivity component. In the first model, the sensitivity (α) is a constant with an inverse time dimension (s^{-1}), whereas the second model uses two special case sensitivity components, α_1 and α_2, to address response variation during close and long distance headway conditions. Numeric values for each of these parameters are estimated for individual drivers by using field experiment data.

$$\ddot{x}_{n+1}(t+\Delta t) = \alpha[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{3}$$

$$\ddot{x}_{n+1}(t+\Delta t) = \alpha_{1or2}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{4}$$

In the third model, shown in (5), *m*=0 and *l*=1. Here, the relationship between the response and the stimulus (speed difference) is nonlinear due to the denominator of the sensitivity component of the equation. In this relationship, drivers are believed to become more sensitive as the vehicles come closer. The sensitivity component $\alpha_{1,0}$ is a speed term that was also estimated by field experiment data.

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_{l,0}}{[x_n(t) - x_{n+1}(t)]}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{5}$$

In the fourth model, shown by Eq. 6, both the speed and the distance headway factors affect the stimulus-response relationship to a certain degree, and both *m* and *l* are equal to unity. The sensitivity component consists of three components: a dimensionless constant $\alpha_{1,1}$, the speed of a following vehicle, and vehicle separation. [5].

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_{1,1}[\dot{x}_{n+1}(t+\Delta t)]}{[x_n(t) - x_{n+1}(t)]}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{6}$$

DATA COLLECTION

In this study, car-following data of probe vehicles equipped with DGPS units, as shown in Figure 2, is collected in a 20km multilane motorway section, shown in Figure 1, in South Korea on April 2, 2005 to estimate GM model parameters. The drivers were four young men n their twenties who had at least five year’s driving experience without being involved in any traffic accidents. The vehicles used in the experiment were all passenger cars with automatic gear shifts. The DGPSs used in this study can collect vehicle speed and location on a second-by-second basis with a measurement error lower than 1 m.

In general, data collection for a car-following analysis is accomplished on single lane roadways in which no lane changing maneuver occurs. However, because the motorway, this study is based on, has five lanes in each direction, the drivers involved in the data collection could not avoid the lane changing aspects of other vehicles. Nevertheless, this research could be highly regarded due to absence of car-following behavior researches with DGPS in Korea.

Figure 1 - Data collection area

Figure 2 - Data collection equipment

After field experiment under the conditions described above, five sets of valid data, listed in Table 1, were obtained. In the valid data sets, the speeds of the experiment vehicles changed dramatically due to acceleration or deceleration of the probe cars, which, in general, is required to analyze car-following behavior characteristics.

Table 1 – Valid data sets for car-following analyses

Data set number	Travel time (s)	Leading car	Following car	Average space headway (m)
		Number of DGPS data points	Number of DGPS data points	
1	33s	34 points	34 points	16 m
2	60s	61 points	61 points	16 m
3	48s	49 points	49 points	11 m
4	25s	26 points	26 points	12 m
5	33s	34 points	34 points	32 m

As mentioned above, the DGPS data in this research is collected second-by-second basis, as shown in Table 2. However, 0.1s-based GPS data is needed to estimate GM model parameters in which a reaction time should be calculated at least one decimal place. Therefore, the speed and location data were disaggregated into 0.1 s intervals using the second-based acceleration or deceleration data of the two vehicles, which in listed Table 3.

A hypothesis of constant acceleration or deceleration within 1 s is required in order to disaggregate 1 s-based data into the 0.1 s-based one. To verify this hypothesis, the distances of the each probe vehicle from the starting point of the following probe car were calculated using the disaggregate acceleration (or deceleration) and the speed. From the comparison, the difference between the calculated values and the observed ones was only 0.3 m ((75.3-59.8)-15.2) after 3 s had elapsed. This implies little disadvantages when using the disaggregated data for a car-following behaviour analysis exist.

Table 2 – DGPS raw data of valid data set 1

GPS time	Leading car			Following car			Distance difference (m)
	Speed (m/s)	Y-coordinate	X-coordinate	Speed (m/s)	Y-coordinate	X-coordinate	
06:38:40pm	20.9	462769.5	173631.6	21.5	462761.6	173647.8	18.0
06:38:41pm	20.1	462778.5	173613.4	20.7	462771.0	173628.9	17.2
06:38:42pm	18.3	462787.1	173596.2	19.5	462780.0	173610.9	16.3
06:38:42pm	16.8	462794.9	173580.7	17.7	462788.3	173594.2	15.2
06:38:43pm	15.5	462802.2	173566.3	15.9	462795.7	173579.2	14.5
06:38:44pm	13.6	462808.7	173553.3	14.1	462802.4	173565.8	14.0
06:38:45pm	11.4	462814.2	173542.2	12.5	462808.2	173553.9	13.1
06:38:46pm	9.1	462818.7	173533.0	10.8	462813.4	173543.5	11.7
06:38:48pm	6.9	462821.3	173525.5	9.1	462817.9	173534.7	9.8
06:38:49pm	6.5	462821.6	173518.7	7.7	462821.3	173527.0	8.2
06:38:50pm	5.9	462818.6	173513.6	6.5	462822.4	173520.1	7.6

Table 3 – Example of disaggregated data of valid data set 1

Time (s)	Leading car			Following car		
	Acceleration (㎨)	Speed (㎧)	Distance (m)	Acceleration (㎨)	Speed (㎧)	Distance (m)
0.0	-	20.8744	18.0143	-	21.5444	0.0000
0.1	-0.7375	20.8007	20.0981	-0.8808	21.4564	2.1500
0.2	-0.7375	20.7269	22.1745	-0.8808	21.3683	4.2913
0.3	-0.7375	20.6532	24.2435	-0.8808	21.2802	6.4237
0.4	-0.7375	20.5794	26.3051	-0.8808	21.1921	8.5473
0.5	-0.7375	20.5057	28.3594	-0.8808	21.1040	10.6621
0.6	-0.7375	20.4319	30.4063	-0.8808	21.0159	12.7681
0.7	-0.7375	20.3582	32.4458	-0.8808	20.9279	14.8653
0.8	-0.7375	20.2844	34.4779	-0.8808	20.8398	16.9537
0.9	-0.7375	20.2107	36.5027	-0.8808	20.7517	19.0333
1.0	-0.7375	20.1369	38.5200	-0.8808	20.6636	21.1040
1.1	-1.8225	19.9547	40.5246	-1.1178	20.5518	23.1648
1.2	-1.8225	19.7724	42.5110	-1.1178	20.4401	25.2144
1.3	-1.8225	19.5902	44.4791	-1.1178	20.3283	27.2528
1.4	-1.8225	19.4079	46.4290	-1.1178	20.2165	29.2801
1.5	-1.8225	19.2257	48.3607	-1.1178	20.1047	31.2961
1.6	-1.8225	19.0434	50.2742	-1.1178	19.9929	33.3010
1.7	-1.8225	18.8612	52.1694	-1.1178	19.8812	35.2947
1.8	-1.8225	18.6789	54.0464	-1.1178	19.7694	37.2772
1.9	-1.8225	18.4967	55.9052	-1.1178	19.6576	39.2486
2.0	-1.8225	18.3144	57.7457	-1.1178	19.5458	41.2088
2.1	-1.5003	18.1644	59.5697	-1.8881	19.3570	43.1539
2.2	-1.5003	18.0144	61.3786	-1.8881	19.1682	45.0802
2.3	-1.5003	17.8644	63.1726	-1.8881	18.9794	46.9875
2.4	-1.5003	17.7143	64.9515	-1.8881	18.7906	48.8760
2.5	-1.5003	17.5643	66.7154	-1.8881	18.6018	50.7457
2.6	-1.5003	17.4143	68.4644	-1.8881	18.4130	52.5964
2.7	-1.5003	17.2643	70.1983	-1.8881	18.2242	54.4283
2.8	-1.5003	17.1142	71.9172	-1.8881	18.0354	56.2412
2.9	-1.5003	16.9642	73.6211	-1.8881	17.8466	58.0353
3.0	-1.5003	16.8142	75.3100	-1.8881	17.6578	59.8106

MODEL CALCULATION

In this section, the reaction time (T) and sensitivity (α) of GM1 model are estimated using the disaggregated DGPS data. The methodology used in this research is similar to those of the existing study [1], but the difference is the evaluation index for estimating optimal parameters. In the previous research, residual error of regression equation was used, whereas Absolute Percent Error (APE) has been used in this research.

The sensitivity (α) values corresponding to the reaction time varied from 0.3 s to 2.2 sec – the minimum and maximum reaction time assumed in this paper – in steps of 0.1 s were calculated. Subsequently, the acceleration (or deceleration) of the following car was calculated with the reaction time and sensitivity. Finally, the optimal reaction time and sensitivity were decided at the point where the APE for acceleration is minimum. The values given in Table 4 represent the analysis results of the valid data set 1 given in Table 1. The graphical description of the APEs for the acceleration is presented on the left side of Figure 3. As shown in Table 4 and Figure 3, the APE has a minimum value of 235.6 at the reaction time of 1.4 s and sensitivity of 0.69. The difference between the observed and calculated acceleration are represented on the right side of Figure 3. The GM1 model parameters for the other four valid data sets were estimated using the methodology described above, and they are listed in Table 5.

Table 4 – GM1 model parameter calculation for data set 1

Reaction time (T)	Acceleration APE(%)	Speed (km/h)	Distance (m)	Sensitivity(a) (sec^{-1})	C value (T×a)
0.3	352.9	56.7	23.1	0.714	0.21
0.4	376.3	55.9	22.8	0.720	0.29
0.5	341.4	55.9	21.7	0.668	0.33
0.6	391.1	57.4	22.9	0.741	0.44
0.7	333.4	55.9	21.5	0.686	0.48
0.8	345.5	55.0	21.3	0.692	0.55
0.9	357.6	54.2	21.1	0.699	0.63
1.0	338.8	56.1	20.3	0.653	0.65
1.1	313.0	56.2	20.6	0.662	0.73
1.2	287.2	56.2	20.8	0.671	0.81
1.3	261.4	56.3	21.0	0.680	0.89
1.4	235.6	56.3	21.2	0.690	0.97
1.5	400.4	57.3	20.4	0.654	0.98
1.6	457.3	54.2	20.9	0.728	1.17
1.7	341.3	58.3	22.8	0.816	1.39
1.8	394.4	55.9	19.7	0.644	1.16
1.9	664.9	62.8	25.0	0.955	1.81
2.0	497.0	55.6	21.4	0.762	1.52
2.1	603.7	60.6	24.2	0.963	2.02
2.2	989.9	77.8	36.7	1.685	3.71

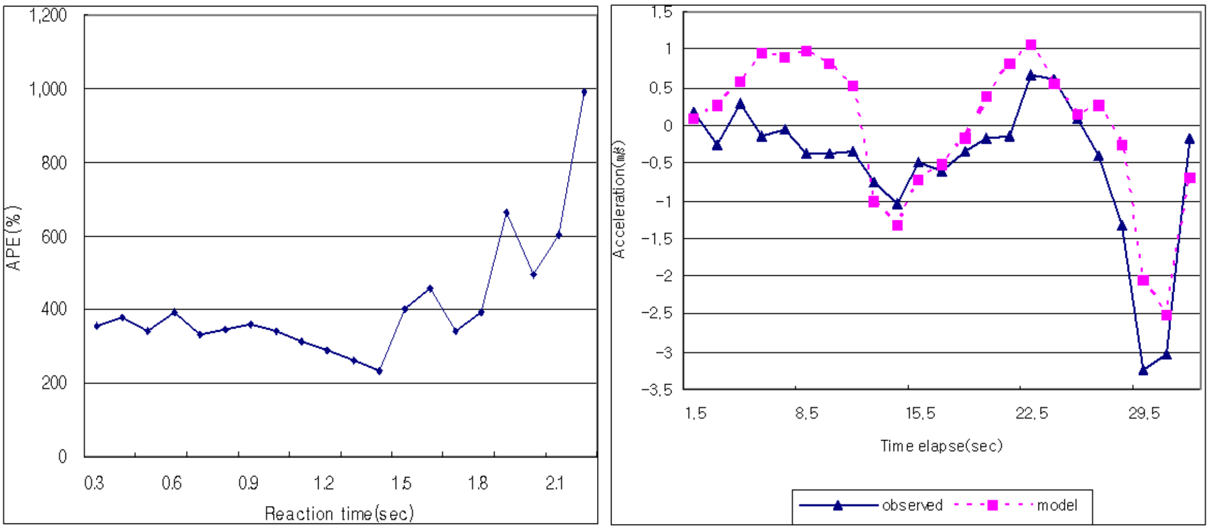

Figure 3 – GM1 model parameter estimation and acceleration comparison

Table 5 – Estimated GM1 model parameters and stability limits

Data set number	Reaction time (T) (s)	Sensitivity(a) (s^{-1})	C value (T×a)	Average space headway (m)
1	1.4	0.69	0.97	16
2	1.4	1.98	2.78	16
3	1.1	1.84	2.03	11
4	1.0	2.29	2.29	12
5	0.8	0.66	0.52	32

C value	Local stability	Asymptotic stability
0.0 … (0.37)	Non oscillatory	Damped Oscillatory
0.5, 1.0, 1.5 … (1.57)	Damped Oscillatory	Increased Oscillatory
2.0	Increased Oscillatory	Increased Oscillatory

Source: Reference [5] p. 180

As mentioned previously, because data collection in this study was conducted on a multilane roadway, the driver in the following vehicle needed to be aggressive in order to be unaffected by the lane changing maneuvers of other vehicles. This aspect has been verified in the analysis results listed in Table 5. The C-values, calculated by multiplying the reaction time (T) and the sensitivity (α), lie in the range of 0.52 to 2.78, which implies that the traffic flow of the two experiment cars is more or less unstable (see the reference values in Table 5).

Table 6 – Comparison of GM1 model parameters

Classification		GM	Brian	This study
Sensitivity(α) (1/s)	Minimum	0.17	0.25	0.66
	Average	0.37	0.46	1.49
	Maximum	0.74	0.70	2.29
Reaction time(T) (s)	Minimum	1.00	0.70	0.80
	Average	1.55	1.01	1.14
	Maximum	2.20	1.25	1.40
Space headway (m)	Minimum	26	18	11
	Average	41	29	17
	Maximum	60	46	32

The GM1 model parameters estimated in this research were compared with some existing ones [1, 6], as shown in Table 6. As a result, the sensitivity coefficients are significantly higher than the existing ones, the reaction time is slightly shorter, and the space headways are considerably closer. These results are consistent with the hypothesis that closer space headways lead to shorter reaction times and higher sensitivities. Another interesting point is that the space headways of Brian's and this study are closer than those of GM researchers' study. This aspect is presumably caused by the improved acceleration and deceleration performance of cars nowadays, as compared to those of cars in the 1970s, which makes drivers, especially younger drivers, exhibit more aggressive driving patterns.

CONCLUSIONS AND FUTURE STUDY

In this paper, GM1 model parameters are estimated using DGPS data on an uninterrupted multilane facility in Korea. In this car-following analysis, DGPS has proven to have two principal advantages compared with other tools, such as cables and reels or video frames. For one thing, installation of a DGPS unit is easy and simple, which makes data collection be possible in various traffic, driver and roadway conditions. Second, a DGPS unit produces data in a digitalized format that makes data analysis a time saving work.

The results of this research are a little different from the results from existing studies. As described earlier, the difference presumably results from the data collection condition of multilane roadway and drivers with aggressive driving pattern. In the future, it is probably required to collect car-following data under various driver, roadway, and traffic conditions to develop more precise and universal car-following model for Korean roadways.

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