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안전성 제고를 위한 버스전용차로 디자인 연구

양철수*
광주발전연구원 도시환경연구실

A Study on the Safety-Maximizing Design of Exclusive Bus Lanes

YANG, Chulsu*
Urban and Environmental Department, Gwangju Development Institute, Gwangju 506-802, Korea

Abstract

Exclusive bus lane (EBL) is typically located in the roadway median, and is accessed by weaving across the GPLs(general purpose lanes) before entering from the left lane of the GPLs. To maximize the potential for successful EBL operations, a critical design issue that requires special attention is the length of bus weaving section before entering EBL. The process of developing guidelines for the length of bus weaving section can be supported by a sensitivity analysis of performance measure (safety) with respect to the bus weaving distance. However, field data are difficult to obtain due to inherent complexity in creating performance measure (safety) samples under various interesting flows and bus weaving distance that are keys to research success. In this paper, VISSIM simulation is applied to simulate the operation of roadway weaving areas with EBL, and based on vehicle trajectory data from microscopic traffic simulation models, the Surrogate Safety Assessment Model (SSAM) computes the number of surrogate conflicts (or degree of safety) with respect to the bus weaving distance. Then, a multiple linear regression (MLR) model using safety data (number of surrogate conflicts) is developed. Finally, guidelines for bus weaving distance are established based on the developed MLR. Developed guidelines explicitly indicate that a longer bus weaving distance is required to maintain desired safety as weaving volume increases.

도로 중앙에 위치한 버스전용차로는 일반차로상에서 복수의 차로변경을 통해 일반차로의 가장왼쪽 차로에서 버스전용차로로 진입할 수 있다. 성공적인 버스전용차로 운영을 위해서 특히 주목해야 할 사항은 도로 진입구에서 도로중앙에 위치한 버스전용차로 진·출입구간까지의 적당한 차로변경구간길이이다. 차로변경길이 증감에 대한 안전민감도 분석을 통해 적절한 차로변경구간길이에 대한 지침을 도출할 수 있다. 하지만 차로변경구간길이에 대한 지침을 도출하기 위한 과정은 다양한 교통량 및 차로변경구간길이와 안전과의 상관관계 현장데이터가 필요하기 때문에 어려움이 있다. 본 연구는 미시적 교통시뮬레이션 프로그램(VISSIM)을 통해 차량의 흐름을 시뮬레이션하고, 시뮬레이션된 각 차량의 궤도(trajectory) 데이터를 기초로 Surrogate Safety Assessment Model (SSAM)을 이용하여 차로변경구간길이 증감에 따른 차량들간의 상충횟수(또는 안전의 정도)를 조사한다. 그리고 차로변경구간길이와 상충횟수의 관계를 다중선형회귀모형으로 정립한다. 마지막으로 다중선형회귀모형을 통해 차로변경구간길이에 대한 디자인 지침을 도출한다. 디자인 지침은 차로변경 교통량이 증가할수록 안전을 확보하기 위해 증가된 차로변경길이가 요구됨을 보여준다.

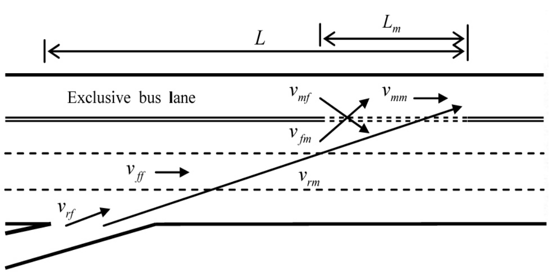
Key Words

Exclusive bus lanes, Arterial, Route, Simulation, Safety
버스전용차로, 간선도로, 노선, 시뮬레이션, 안전

* : Corresponding Author
csyang@gji.re.kr, Phone: +82-62-940-0545, Fax: +82-62-940-0524

Ⅰ. INTRODUCTION

The exclusive bus lane (EBL) can provide a good opportunity to reduce traffic congestion by increasing person-carrying capacity and to improve the operation of roadways at a much lower cost than simply providing an equivalent capacity with general purpose lanes (GPLs) only. There are critical design issues that require special attention to maximize the potential for EBL operations. An adequate length of bus weaving section for entering EBL (L in Figure 1) is required for the preservation for safety. Buses access a EBL located in the roadway median by weaving across the general purpose lanes (GPLs) and entering the EBL from the leftmost lane of GPL. In this case, intense lane-changing maneuvers cause traffic turbulence, which induces special operational problems related to safety. The principal objective of this research is to develop design guidelines for the length of bus weaving section for entering EBL between the entrance ramp and the EBL access opening (L in Figure 1).



L : length of bus weaving section for entering EBL
L_m : EBL opening length
V_{ff} : traffic volume from the GPLs to the GPLs
V_{fm} : traffic volume from the GPLs to the EBL
V_{mf} : traffic volume from the EBL to the GPLs
V_{rf} : traffic volume from the ramp to the GPLs
V_{rm} : traffic volume from the ramp to the EBL
V_{mm} : traffic volume from the EBL to the EBL

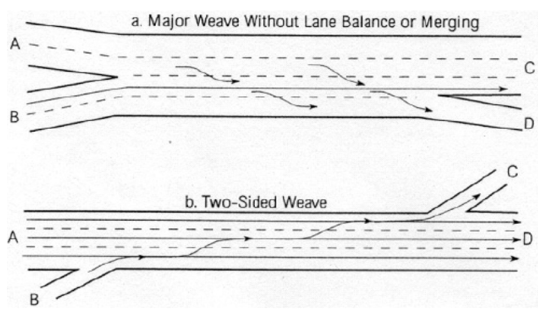
<Figure 1> Lane configuration and traffic movements

Ⅱ. LITERATURE REVIEWS

1. Weaving Area Analysis in 2000 Highway Capacity Manual (2000 HCM)

The traffic weaving from an entrance ramp to the general purpose lanes across to the EBL are effectively modeled as a two-sided Type C weave as based on the 2000 Highway Capacity Manual (HCM). A typical example of Type C weaves is shown in Figure 2. A special case of Type C weaves is the two-sided weave, shown in Figure 2. Here, the flow from ramp to ramp is the smaller weaving flow, and the larger weaving flow is the through mainlane flow. The two-sided weave can serve in the analysis of the flow on the GPLs between entrance or exit ramps on the right to the access points for the EBL on the left.

The 2000 HCM methodology has been calibrated for the major weave without lane balance or merging (standard Type C weave) but not for the two-sided Type C weave. As such, the 2000 HCM can provide only the roughest of approximations when applied to a two-sided weave.



<Figure 2> Type C weaves.

2. Other Weaving Research

Existing design guidelines provide a range of answers, but are likely based on operational experience rather than a thorough analysis of the weaving area. Guidelines in literature are listed below:

- the minimum length of weaving section (L) is 150m per lane (Caltrans, 1991),
- the minimum length of weaving section (L) is 150m per lane, and the desired one is 300m per lane (Fuhs, 1990), and
- the suggested minimum length of weaving section (L) is 750m (Turnbull and Capelle, 1998).

Williams (2010) developed a more detailed set of capacity-based design guidelines using VISSIM simulation, which was extensively calibrated using data collected on IH 635 (LBJ Expressway) in Dallas. Capacity-based design guidelines are also found in the literature of Yang et al.(2010).

Ⅲ. RESEARCH APPROACH

VISSIM is a microscopic, stochastic, and time step-based traffic simulation model which uses car following and lane change routines. It is capable of assessing traffic and transit operations for a wide variety of traffic conditions. Williams (2010) calibrated VISSIM parameters using data from an urban Texas expressway currently operating with the high-occupancy vehicle (HOV) lane as shown in Table 1. A wide range of flow conditions was considered, the flows of interest including the flows in the GPLs, the ramps, as well as the flow weaving across the GPLs. VISSIM, which calibrated by Williams (2010), is used in this research to simulate expressway operations as buses weaved across the GPLs enter the EBL.

- Lane change defines the distance that a driver begins to attempt to change lanes before reaching the next connector of a route.
- Maximum deceleration for own defines the maximum acceptable deceleration for the vehicle changing lanes. The higher this number (in absolute terms), the greater the aggressiveness of the lane change.
- Maximum deceleration for the trailing vehicle defines the maximum deceleration for the trailing vehicle.
- Waiting time before diffusion defines the maximum amount of time a vehicle can wait at the emergency stop position waiting for a gap to change lanes. Once this time is reached, the vehicle is removed from the network (diffusion).
- Based on the safety distance reduction factor, the resulting shorter safety distance is estimated as (original safety distance × reduction factor).
- CC0 (standstill distance) defines the desired distance between stopped cars.
- CC1 (headway time) defines time headway that a driver wants to keep at a certain speed.
- CC2 (following variation) defines the longitudinal oscillation in distance between the leading and trailing vehicles. This distance ranges from the desired safety distance to the sum of the desired safety distance and following variation.
- CC3 (threshold for entering following) defines how many seconds before reaching the safety distance the driver starts to decelerate.
- CC4 and CC5 (following thresholds) control the speed differences between the lead and following vehicles. Smaller (absolute) values represent a quicker response by the following vehicle to speed changes of the lead vehicle. CC4 is used for negative speed differences, while CC5 is used for positive speed differences. The absolute

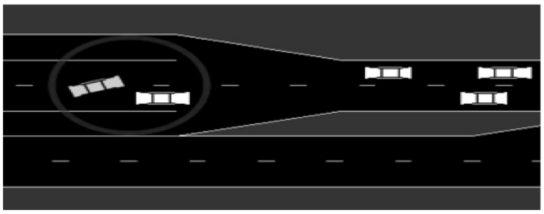
<Table 1> Calibrated VISSIM Parameters

Parameter	Default Parameter	Calibrated Parameter
Lane change	656 ft	2750
Maximum deceleration for own	-13.1 ft/s^2	-16.0 (-20)
Maximum deceleration for the trailing vehicle	-9.8 ft/s^2	-13.0 (-17)
Waiting time before diffusion	60 s	12 (30)
Safety distance reduction factor	0.6	0.40 (0.0)
CC0 (Standstill distance)	4.9 ft	6.0
CC1 (Headway time)	0.90 s	0.95
CC2 (Following variation)	13.1 ft	16.0(30)
CC3 (Threshold for entering following)	-8.0	-7.0
CC4 (Negative following threshold)	-0.35	-0.60
CC5 (Positive following threshold)	0.35	0.60

( ) : Ramp junction only

values of these parameters are typically equal, implying the same response for negative and positive speed differences.

The Federal Highway Administration-sponsored SSAM is a tool being developed for the analysis of conflicts using simulated results from microsimulation. The SSAM software is designed to perform statistical analysis of vehicle trajectory data, which is output from microsimulation. In the SSAM software, a “conflict” is defined as an observable situation where two or more vehicles approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged as shown in Figure 3.



<Figure 3> Conflict image (Source: SSAM software)

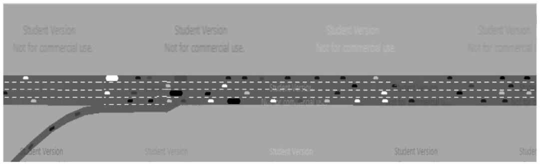
There are the four types of conflicts as crossing, rear-end, lane-change and unclassified. Conflict type is generally based on the conflict angle:

- Crossing: |conflict angle|〉 85°
- Rear-end: |conflict angle|〈 30°
- Lane-change: 30° ≤ |conflict angle| ≤ 85°
- Unclassified: Conflict angle unknown

The logic for conflict classification of these types is summarized as follows. The conflict angle is expressed from the perspective of the first car to arrive at the collision point. The conflict with an angle of |conflict angle|〉 85° such as ‘Crossing’ indicates that two vehicles are on perpendicular paths. The conflict with a small angle of |conflict angle|〈 30° such as ‘Rear-end’ indicates that the vehicles are running on the same lane, whereas the conflict with an angle of 30° ≤ |conflict angle| ≤ 85° indicates that one of vehicles is on lane change.

The analysis of traffic conflicts was initiated to assess the safety of a location, with the understanding that the number of conflicts is correlated with safety index. In other words, the safety analysis in the SSAM is correlated with the simulation analysis in order to provide an indication of safety characteristics (e.g., likelihood of crash rates). In this research, the SSAM in accordance with VISSIM simulation is utilized to estimate the safety degree of weaving areas with the exclusive bus lane (EBL) (see Figures 4 and 5).

The process of developing design guidelines for the length of weaving section can be achieved by a sensitivity analysis of safety with respect to the length of weaving section (or weaving distance). This is not feasible with field data because the replicated sampling of safety data under various interesting flows and weaving distances are the keys for research



<Figure 4> Image of VISSIM simulation in a weaving area

<Figure 5> Location of conflicts in a weaving area: triangle (conflict of rear-end), rectangle (conflict of lane-change)

success. A VISSIM simulation model, which was calibrated by Williams et al. (2010), is used as a standard to develop design guidelines.

The Surrogate Safety Assessment Model (SSAM) is a software application designed to perform statistical analysis of vehicle trajectory data, which is output from VISSIM simulation. The SSAM is utilized to estimate the degree of safety in the weaving area, which is presented by a number of conflicts. The safety analysis in the SSAM is correlated with simulation in order to provide an indication of safety characteristics (e.g., likelihood of crash rates) under varying geometric and operating conditions.

Safety data (number of conflicts) is modeled using linear functions as unknown model parameters are estimated from the data. In other words, a multiple linear regression (MLR) using safety data (number of conflicts) is developed. Finally, guidelines for length of weaving section are established based on the developed MLR.

Ⅳ. SCREENING EXPERIMENTS

1. Screening Experiments

A two-phase approach is employed, where screening experiments are employed first to explore potentially important effects, and then, a second set of experiments is conducted to focus on the important effects and develop a MLR. Screening experiments are performed to find and filter factors of the length of weaving section, the EBL opening length, and traffic volumes that do not have effects on safety (# of conflicts). Only the important factors are considered to develop the MLR.

In this research, fractional factorial experiments are used to conduct screening experiments. The advantage of the fractional design is that it reduces the effort in running experiments by observing a fraction of the treatment combinations. Small experiments with only two levels per factor are conducted to study the main effects and two-factor interaction effects. In the design of experiments, the smallest fractional factorial design is desired. Since VISSIM is stochastic in nature, multiple replications are performed to enable estimation of the random error variance. An analysis of variance (ANOVA) model is used to identify the statistically significant main and two-factor interaction effects. As stated, only those factors with significant effects on safety (# of conflicts) are considered for the next phase of experiments to develop the MLR.

2. Design of Screening Experiments

The design of screening experiments for safety with lane configuration as shown in Figure 1 is given below:

- performance measurement: safety (# of conflicts)
- replications: 3
- experimental design: two-level fractional factorial experiment
- two levels of the factors:
  - Factor A: EBL opening length (L_m) with

<Table 2> Number of Conflicts

Treatment	L_m	L	V_{rm}	V_{fm}	V_{mf}	V_m	V_f	Number of Conflicts		
								Replication 1	Replication 2	Replication 3
1	1000	2000	100	200	200	800	6000	23	23	13
2	1000	2000	100	200	200	1200	8000	97	161	109
3	1000	2000	100	200	600	800	8000	79	222	190
4	1000	2000	100	200	600	1200	6000	36	68	23
5	1000	2000	100	400	200	800	8000	81	77	121
6	1000	2000	100	400	200	1200	6000	33	51	17
7	1000	2000	100	400	600	800	6000	28	30	21
8	1000	2000	100	400	600	1200	8000	112	186	327
9	1000	2000	400	200	200	800	8000	924	1148	1113
10	1000	2000	400	200	200	1200	6000	145	89	151
11	1000	2000	400	200	600	800	6000	143	113	120
12	1000	2000	400	200	600	1200	8000	2847	2213	2494
13	1000	2000	400	400	200	800	6000	53	58	172
14	1000	2000	400	400	200	1200	8000	1713	1283	1597
15	1000	2000	400	400	600	800	8000	1606	2219	1933
16	1000	2000	400	400	600	1200	6000	189	151	267
17	1000	4000	100	200	200	800	8000	55	40	18
18	1000	4000	100	200	200	1200	6000	9	21	13
19	1000	4000	100	200	600	800	6000	12	41	44
20	1000	4000	100	200	600	1200	8000	121	71	93
Omit										
61	1500	4000	400	400	200	80	6000	30	33	28
62	1500	4000	400	400	200	1200	8000	249	233	269
63	1500	4000	400	400	600	800	8000	172	219	186
64	1500	4000	400	400	600	1200	6000	76	43	95

level 1 = 300 m, level 2 = 450 m

- Factor B: length of weaving section (L) with level 1 = 600 m, level 2 = 1200 m
- Factor C: ramp to EBL volume (v_{rm}) with level 1 = 100 (vehicles/hr), level 2 = 400 (vehicles/hr)
- Factor D: GPLs to EBL volume (v_{rm}) with level 1 = 200 (vehicles/hr), level 2 = 400 (vehicles/hr)
- Factor E: EBL to GPL volume (v_{mf}) with level 1 = 200 (vehicles/hr), level 2 = 600 (vehicles/hr)
- Factor F: EBL volume (v_m) with level 1 = 800 (vehicles/hr), level 2 = 1200 (vehicles/hr)
- Factor G: GPL volume (v_f) with level 1 = 6000 (vehicles/hr), level 2 = 8000 (vehicles/hr)

The tabulated results of the screening experiments for safety are shown in Table 2. The SAS output for the ANOVA shows the significance of the main effects and two-factor interaction effects. In the Table 3, significant effects with p-values less than a significance level of 0.01 are highlighted. The SAS has four options to produce sums of squares as Type I, II, III and IV. The selected option of the marginal Sums of Squares (Type III SS) as shown in Table 3 do not depend upon the order in which effects are specified in the model. The Type III SS are preferable to identify the statistically significant main and two-factor interaction effects.

In the safety analysis, the most significant main effects among the sources (main effects and two-factor interaction effects in Table 3)

<Table 3> ANOVA Table for Safety

Source	DF	Type III SS	Mean Square	F Value	Pr 〉F
L_m	1	38931.02	38931.02	0.63	0.4272
L	1	8043400.02	8043400.02	130.91	〈.0001
V_{rm}	1	10846156.02	10846156.02	176.52	〈.0001
V_{fm}	1	3383.52	3383.52	0.06	0.8148
V_{mf}	1	950907.00	950907.00	15.48	0.0001
V_m	1	315090.02	315090.02	5.13	0.0249
V_f	1	10588165.33	10588165.33	172.33	〈.0001
L_m*V_{rm}	1	9213.02	9213.02	0.15	0.6991
L_m*V_{fm}	1	450.19	450.19	0.01	0.9319
L_m*V_{mf}	1	26885.33	26885.33	0.44	0.5092
L_m*V_m	1	22059.19	22059.19	0.36	0.5499
Lm*Vf	1	27648.00	27648.00	0.45	0.5033
L*V_{rm}	1	6625331.02	6625331.02	107.83	〈.0001
L*V_{fm}	1	12448.52	12448.52	0.20	0.6532
L*V_{mf}	1	532565.33	532565.33	8.67	0.0037
L*V_m	1	108966.02	108966.02	1.77	0.1848
L*V_f	1	6424033.33	6424033.33	104.55	〈.0001
V_{rm}*V_{fm}	1	82.69	82.69	0.00	0.9708
V_{rm}*V_{mf}	1	668824.08	668824.08	10.89	0.0012
V_{rm}*V_m	1	206850.02	206850.02	3.37	0.0684
V_{rm}*V_f	1	7702416.33	7702416.33	125.36	〈.0001
V_{fm}*V_{mf}	1	9520.33	9520.33	0.15	0.6944
V_{fm}*V_m	1	10413.52	10413.52	0.17	0.6811
V_{fm}*V_f	1	40.33	40.33	0.00	0.9796
V_{mf}*V_m	1	341.33	341.33	0.01	0.9407
V_{mf}*V_f	1	759278.52	759278.52	12.36	0.0006
V_m*V_f	1	154814.08	154814.08	2.52	0.1144

<Table 4> Summary of the Screening Experiment

Significant main effects	Significant two-factor interaction effects	Selected Factors considered as predictor variable in the MLR
L, V_{rm}, V_{mf}, V_f	L*V_{rm}, L*V_{mf}, L*Vf, V_{rm}*V_{mf}, V_{rm}*V_f, V_{mf}*V_f	L, V_{rm}, V_{mf}, V_f

are L, v_{rm}, and v_f. Also, the most significant interactions occur between L, v_{rm} and v_f, which are identified as the significant main effects. As discussed previously, the screening experiments are performed to filter factors that do not have significant effects on safety (# of conflicts).

The important factors, which have either the main effects or the two-factor interaction effects with p-values less than a significance level of 0.01, are considered as predictor variables in the MLR. Table 4 shows the summary of screening experiments for safety. The statistically significant factors of L, v_{rm}, v_{mf}, and v_f are selected as predictor variables in the MLR.

V. DEVELOPMENT OF MLR

In this section, a MLR model is developed based on the simulated data with input factors filtered in the screening experiment. Orthogonal arrays for the experiments are employed. An orthogonal array is a combinational arrangement useful for conducting experiments to determine the optimum mix of the number of factors in a product to maximize the yield of experiments by avoiding redundancy in the experiment. An orthogonal array experimental design is in fact a fractional factorial design that allows more than two levels for each factor.

1. Experiments for Safety with Screened Factors

The experiments are conducted with the screened factors and the middle value of the insignificant factors as shown below:

Screened Factors

- Factor A: length of weaving section (L) is increased from 600m to 1200m
- Factor B: ramp to EBL volume (v_{rm}) is increased from 100 to 400 vehicles/hr
- Factor C: EBL to GPL volume (v_{mf}) is increased from 200 to 600 vehicles/hr
- Factor D: GPL volume (v_f) is increased from 6000 to 8000 vehicles/hr

Insignificant Factors

- L_m =375m
- v_r =500 vehicles/hr
- v_{fm} =300 vehicles/hr
- v_m =1000 vehicles/hr

Each continuous factor is represented by a

<Table 5> Number of Conflicts

Treatment	L	V_{rm}	V_{mf}	V_f	Number of Conflicts		
					Replication 1	Replication 2	Replication 3
1	600	100	200	6000	17	23	9
2	700	150	400	7667	94	58	75
3	800	200	467	8000	73	64	107
4	900	250	533	6333	28	17	11
5	1000	300	600	6667	51	22	17
6	1100	350	267	7000	57	47	82
7	1200	400	333	7333	120	113	83
8	600	150	267	6333	40	74	75
9	700	250	333	8000	187	103	160
10	800	350	200	7333	32	84	112
11	900	200	600	7000	17	34	8
12	1000	100	467	7667	19	30	16
13	1100	400	400	6667	53	21	57
14	1200	300	533	6000	15	52	49
15	600	200	333	6667	48	61	117
16	700	350	600	6000	58	77	34
17	800	300	400	6333	45	50	38
18	900	400	200	7667	61	116	100
19	1000	250	267	7333	17	68	73
20	1100	100	533	8000	46	63	23
21	1200	150	467	7000	9	10	18
22	600	250	400	7000	143	149	129
23	700	200	533	7333	84	85	63
24	800	400	267	6000	42	42	37
25	900	350	467	6667	40	64	14
26	1000	150	200	8000	18	17	52
27	1100	300	333	7667	66	65	70
28	1200	100	600	6333	26	7	25
Omit							
46	900	100	400	73 3	23	41	7
47	1000	350	333	6333	29	23	50
48	1100	250	467	6000	11	41	60
49	1200	200	267	7667	60	38	84

discrete series of values with a certain increase known as a level. For example, the length of weaving section (L), which has a lower limit of 600m and an upper limit of 1200m, has 7 levels of 600m, 700m, 800m, 900m, 1000m, 1100m and 1200m. Safety analysis using SSAM in accordance with VISSIM simulation are then performed. The result of safety analysis is shown in Table 5.

2. Preliminary Model

The multiple linear regression (MLR) is a method used to obtain a best fit equation. A general MLR is given by an equation $Y_i = \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_p X_{pi} + \varepsilon_i$, where Y_i is the response variable for observation I, p is the number of predictors, β is a p-dimensional model parameter and statistical estimation in MLR focuses on β, X_k is the predictor, and ε_i is a random error in Y for observation i.

The method of least squares is used to estimate the model parameters using the SAS program. The result of regressing predictors for safety based on Table 5 is shown in Table 6 as a SAS output. From the SAS output as shown in Table 6, the regression function for safety is obtained as

$$\hat{y} = -0.17438(L) + 1.06827(v_{rm}) + 0.64712(v_{mf}) + 0.16248(v_f) - 1012.6 \quad (1)$$

3. Transformation and Adding Quadratic and Interaction Terms

The linear regression is based on the following assumptions:

a. The current MLR model form is reasonable,
b. The residuals have constant variance,
c. The residuals are normally distributed,
d. There are no outliers, and
e. The variables are not highly correlated with each other.

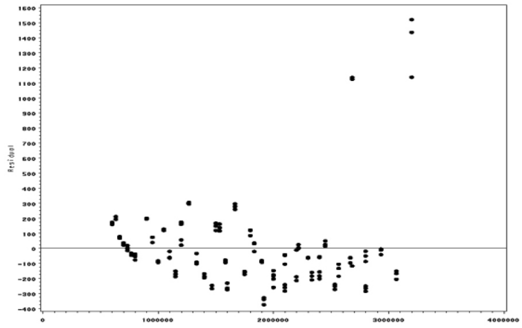
Assumptions b and c are evaluated. Reviewing the original response vs. predictor scatterplot reveals the appearance of funnel shapes possibly indicating violation of the constant variance assumption(see Figure 6). A normality test is conducted based on the normality plot to check whether the residuals are normally distributed. The normality plot does not show a linear trend, as illustrated in Figure 7. This result indicates that the normality assumption is violated.

The violation of model assumptions as stated above requires a need for remedial actions. It is decided to pursue transformations to satisfy the model assumptions. Four types of transformations with y, ln(y), 1/y, $y^{0.5}$ and $1/y^{0.5}$, are attempted. The ln(y)-transformation, which improves model assumptions, is selected. Then, quadratic terms to the ln(y)-transformed model are added in a standardized form to improve the model's quality of fit.

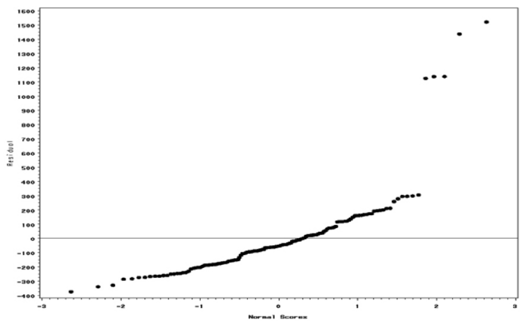
<Table 6> Estimated Parameters for Safety Parameter

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr 〉|t|	Variable
Intercept	1	-1012.59768	288.97629	-3.50	0.0006	2391582
pred1	1	-0.17438	0.03578	-4.87	〈.0001	1986970
pred2	1	1.06827	0.23856	4.48	〈.0001	1677550
pred3	1	0.64712	0.17898	3.62	0.0004	1093596
pred4	1	0.16248	0.03578	4.54	〈.0001	1725075

notion: pred1-4 are denoted as L, v_{rm}, v_{mf}, and v_f.



<Figure 6> Plot of residuals vs.



<Figure 7> Plot of normality

Based on the SAS output as shown in Table 7, the final transformed regression function for safety is obtained as

$$\hat{y} = \exp[-0.00060683(L) + 0.00558(v_{rm}) + 0.00077444(v_f) + 0.50050\left(\frac{L-3000}{202}\right)^2 + 0.13816\left(\frac{v_f-7000}{674}\right)^2 - 0.17288\left(\frac{L-3000}{202}\right)\cdot\left(\frac{v_f-7000}{674}\right) - 1.74159] \quad (2)$$

The developed MLR model (equation 2) indicates that the most significant main effects are L, v_{rm}, and v_f and the most significant interaction occur between L and v_f.

Ⅵ. DEVELOPMENT OF GUIDELINES FOR THE LENGTH OF WEAVING SECTION

The flow in the GPLs has a large impact on a distance required for weave. This means that the worst condition for weave is under capacity. In other words, the longest weaving distance is required under capacity conditions. Note that the experiment is conducted under a capacity condition on roadway with four GPLs. This paper develops EBL access guidelines assuming that the flow of weaving section capacity is 7,600 (vehicles/hr/lane) as follows.

$$\begin{aligned} \text{Capacity} &= v_f + v_{mf} - v_{fm} + v_r \\ &= 7000 + 400 - 300 + 500 \\ &= 7600 \text{ (vehicles/hr)} \end{aligned}$$

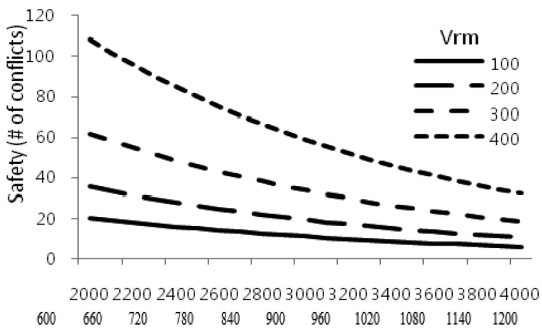
where, $v_r = v_{rm} + v_{rf}$

The guidelines are developed after a sensitivity analysis of safety (# of conflicts) with respect to the length of weaving section (L in Figure 1). Safety with respect to the length of weaving section (L) with various ramp to EBL volumes (v_{rm}) is illustrated as shown in Figure 8, which is obtained from the MLR (equation 2). For the given range of variables, taking a derivative of the developed safety

<Table 7> Estimated Parameters for Safety

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr 〉F
Intercept	-1.74159	0.48977	3.17342	12.64	0.0005
pred1	-0.00060683	0.00006197	24.06169	95.87	〈.0001
pred2	0.00558	0.00041659	44.95960	179.14	〈.0001
pred4	0.00077444	0.00006197	39.18976	156.15	〈.0001
stdx1x1	0.50050	0.04804	27.24372	108.55	〈.0001
stdx4x4	0.13816	0.04804	2.07593	8.27	0.0047
stdx1x4	-0.17288	0.04194	4.26371	16.99	〈.0001

notion: pred1, 2, and 4 are denoted as L, v_{rm}, and V_f.



<Figure 8> Safety vs. and with the middle values of other variables

<Table 8> Recommendations for the length of weaving section (L)

Ramp to EBL volume (v_{rm})	Minimum length of weaving section (L)	
	Four general purpose lanes (m)	Per general purpose lane (m/lane)
100	600	180
200	650	200
300	900	230
400	1200	360

model with respect to the length of weaving section (L) yields the following condition as $d\hat{y}/dL \leq 0$ for any variable. This means that $\hat{y}$ is a monotonically decreasing (safety-increasing) function with respect to the length of weaving section (L) regardless of other variables.

Let a safety-stabilizing point with respect to the length of weaving section (L) be $d\hat{y}/dL = -0.02$ (# of conflicts/m) for the minimum length of weaving section (L). Table 8 shows a safety-stabilizing point with various ramp to EBL volumes (v_{rm}). The recommended minimum length of weaving section (L) varies with the determined stabilizing value. The value suggested in this research can be changed based on engineering judgment for better traffic operations.

Ⅶ. CONCLUSIONS

The exclusive bus lane (EBL), which is typically located in the roadway median, is accessed by weaving across the GPLs. Weaving areas have a major effect on safety. Buses concerned about failing their weaves across the GPL would drive more aggressively. This weaving process is made throughout the entire weaving area. As a result, aggressive driving causes traffic turbulence, which induces frequent vehicle braking. A high level of traffic turbulence is expected in the vicinity of ramps and EBL access points. This aggressive driving behavior lowers the safety of weaving areas.

To maximize the potential for successful EBL operations, the critical design issue that requires special attention is the length of weaving section between the on-ramp (or off-ramp) and EBL access point. The process of developing guidelines is achieved by the sensitivity analysis of safety (# of conflicts) with respect to the length of weaving section with various weaving volume.

The SSAM, designed to perform statistical analysis of vehicle trajectory data, which is output from VISSIM simulation was utilized to estimate the safety of weaving areas with the EBL. A multiple linear regression (MLR) using safety data (number of conflicts) is developed. Finally, Guidelines for the length of weaving section was established based on the developed MLR. In the development of simulation-based guidelines, the safety is improved with an increase of the length of weaving section (L). Also, the ramp to EBL volume is also key factor for safety of the weaving section. Developed guidelines explicitly indicate that a longer bus weaving distance is required as the bus weaving volume increases to maintain desired safety.

알림 : 본 논문은 박사 논문 〈Managed Lanes Weaving and Access Guidelines〉 및 연구보고서 〈Assessment and Validation of Managed Lanes Weaving and Access Guidelines〉의 일부 내용을 수정・보완하여 작성된 것입니다.

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