RESERVED BUS LANES ON URBAN FREEWAYS: A MACROMODEL

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An increasing number of cities are becoming interested in operating buses on reserved lanes so that people can be moved more effectively. This paper develops a person-delay model that can be used in determining the feasibility and practicality for implementing a contraflow freeway bus lane in urban areas. The model deals with peak-hour trips on a six-lane, two-direction freeway, and it uses certain relationships (1) to demonstrate its applicability. The derivation of the model is shown, and the paper discusses, by a step-by-step procedure, how transportation planners can easily use it.

•RESERVED freeway lanes for buses provide a cost-effective approach to bus priorities in radial highway corridors with peak-hour congestion and heavy bus volumes. They apply freeway traffic operations and control techniques to reserve lanes for buses or other designated vehicles (e.g., emergency vehicles, trucks, and multiple-occupancy cars). They involve minimum physical construction, and they can speed bus service where interim access or stations are not required.

APPLICABILITY

Lanes may be reserved for buses in the normal or opposite direction of flow during the morning or evening peak periods; however, contraflow lanes are most common (2).

Contraflow freeway bus lanes are found along I-495 in New Jersey, the Long Island Expressway in New York, and US-101 in Marin County, California. A contraflow lane operation was intermittently operated on the Southeast Expressway, Boston, and one has been proposed for the Hollywood Freeway, Los Angeles. A short, normal flow bus lane exists on the Ninth Street expressway spur in Washington, D.C.

Normal flow bus lanes are usually not practical to implement because, where freeways are free-flowing in the peak periods, lanes are not usually needed to improve bus speeds. Conversely, where freeways operate near or beyond capacity, provision of bus lanes would substantially reduce person-capacity and increase total person-delay. Moreover, normal flow lanes are difficult to enforce.

Contraflow or wrong-way bus lanes can use portions of freeways serving relatively light traffic. Thus, they do not reduce peak directional highway capacity or efficiency. They are an adaptation of the reversible lane concept applied to urban freeways for more than three decades. Costs are minimal, and enforcement is easy because cars are highly visible to police patrols.

Buses can use single contraflow lanes where mixed traffic could not do so safely because (a) the bus lane traffic stream is homogeneous—variation in vehicle performance is minimal and there is no need for overtaking slower vehicles; (b) buses are highly visible to other drivers, especially if emergency flashers are used; (c) professional bus drivers are generally well-trained, experienced, and highly disciplined; and (d) bus lane volumes are relatively low (generally under 200 vehicles per hour); this makes a risk of a collision no greater than on an undivided urban arterial street or rural highway.

Publication of this paper sponsored by Committee on Busways and Bus Lanes.

Contraflow freeway lanes should be applied when the following conditions prevail:

1. The freeway is at least six lanes wide.
2. All normal freeway entrances and exits are to the right of the through traffic lanes.
3. The freeway preferably is illuminated wherever evening contraflow operations are envisioned.
4. Freeway travel in the off-peak direction can be accommodated in the remaining lanes at level of service D or better.
5. The contraflow bus lane generally produces bus passenger time-savings that exceed the time losses imposed on traffic in the opposite direction.

Meeting these broad criteria calls for a high imbalance in peak-hour traffic, an increase in the minimum number of peak-hour buses as traffic in the off-peak direction approaches capacity.

MODELING PERSON-DELAY

Analytical approaches can be used to determine the minimum number of buses required in the flow direction for varying traffic levels in the off-peak direction. The underlying objective is to save bus travelers more time than the time losses that are imposed on other traffic, minimizing total person-delay in both directions.

Assumptions in Model Formulation

The following assumptions underly the person-delay model:

1. The model deals only with peak-hour trips on a six-lane, two-direction freeway.
2. The median lane in the off-peak direction would be used by buses traveling in the peak direction.
3. Car and bus speeds relate to volume-capacity relationships (1, Fig. 9-1).
4. The maximum operating speed for private vehicles is 60 mph.
5. The maximum operating speed for buses when they operate in the contraflow lane is 45 mph.
6. Highway capacity is 1,800 vehicles per lane per hour.
7. In calibrating the model, there are occupancies of 1.5 persons per automobile and 50 persons per bus.
8. Total person-delay with a contraflow bus lane must be equal or less than total person-delay without the lane.

Person-Delay Minimization

The model assumes that the total person-delay after installation of a contraflow bus lane will be less than the person-delay before installation. (The various parameters used in the bus lane model and their notations are given in Table 1.) This concept of total person-delay minimization can be formulated and stated analytically as follows:

$$D_3 + D_4 \leq D_1 + D_2 \tag{1}$$

or conversely,

$$D_1 + D_2 > D_3 + D_4$$

From Eq. 1 it follows that

$$B_1L_1t_1 + A_1M_1t_1 + B_2L_2t_2 + A_2M_2t_2 \geq B_1L_1S_1 + A_1M_1t_3 + B_2L_2t_4 + A_2M_2t_2 \tag{2}$$

$$B_1L_1t_1 - B_1L_1S_1 \geq A_1M_1t_3 - A_1M_1t_1 + A_2M_2t_4 - A_2M_2t_2 + B_2L_2t_4 - B_2L_2t_2 \tag{3}$$

$$B_1L_1(t_1 - S_1) \geq A_1M_1(t_3 - t_1) + A_2M_2(t_4 - t_2) + B_2L_2(t_4 - t_2) \tag{4}$$

Table 1. Key parameters of the bus lane model.

Item	Peak Direction	Off-Peak Direction
Peak-hour buses, number	B_1	B_2
Peak-hour automobiles, number	A_1	A_2
Load factor for buses	L_1	L_2
Load factor for automobiles	M_1	M_2
Bus travel time, with exclusive lane	S_1	—
Vehicle travel time, before implementation of bus lane	t_1	t_2
Vehicle travel time, after implementation of bus lane	t_3	t_4
Total person-delay, before implementation of bus lane	D_1	D_2
Total person-delay, after implementation of bus lane	D_3	D_4

Note: Differences in bus and car travel times can now be defined as follows, assuming that $t \geq 0$:
Bus travel time change = $(\Delta t_1) = t_1 - S_1$.
Automobile travel time change = $(\Delta t_2) = t_4 - t_2$ in the off-peak direction.
Automobile travel time change = $(\Delta t_3) = t_1 - t_3$ in the peak direction.

Table 2. Approximate minimum bus volumes for contraflow bus lane.

TOTAL PEAK DIRECTION (VOLUME PER HOUR)	TOTAL OFF-PEAK DIRECTION (VOLUME PER HOUR) 900	1200	1500	1800	2100	2400	2700	3000	3300	3600	3900	4200	4500	
3600	34	41	90	135	205	288	365	495	693	1701	3130	5355	7594	
3900	14	22	36	54	82	115	146	198	279	680	1252	2142	3030	
4200	10	17	28	42	63	89	112	152	213	524	963	1648	2337	
4500	8	13	21	32	48	68	86	116	163	401	736	1260	1787	I
4800	5	9	14	22	33	46	58	79	111	272	501	857	1215	
5100	4	6	10	15	23	32	41	55	77	189	342	595	844	
5400	2	3	5	8	12	17	22	30	42	102	187	320	484	
6300	1	1	2	3	4	6	8	11	15	37	68	117	166	
7200	1	1	1	2	3	4	5	6	9	23	42	72	103	II
8100	-	-	-	1	1	2	2	4	5	13	23	40	57	
	III													

I These bus volumes exceed most urban bus fleets and fall outside the domain of practical application.

II The domain of practical application--involves hourly bus volumes ranging from about 40 to 200 buses.

III Volumes of under 40 buses per hour do not usually warrant contra-flow lanes.

NOTE: Assumes an occupancy factor of 1.5 and 50 for automobiles and buses, respectively.

$$B_1 \geq \frac{1}{L_1(t_1 - S_1)} [A_1M_1(t_3 - t_1) + A_2M_2(t_4 - t_2) + B_2L_2(t_4 - t_2)] \quad (5)$$

This model assumes that $t_1 > S_1$, $t_1 > t_3$, and $t_4 > t_2$. Therefore,

$$B_1 \geq \frac{1}{L_1\Delta t_1} [A_1M_1(-\Delta t_3) + A_2M_2(\Delta t_2) + B_2L_2(\Delta t_2)] \quad (6)$$

But it can be assumed that $\Delta t_3 \rightarrow 0$ when $B_1 < 200$ and L_2 is negligible for off-peak direction. Therefore,

$$B_1 \geq \left(\frac{1}{L_1\Delta t_1}\right)(A_2M_2\Delta t_2) \quad (7)$$

$$B_1 \geq A_2\left(\frac{M_2}{L_1}\right)\left(\frac{\Delta t_2}{\Delta t_1}\right) \quad (8)$$

(This is approximate.)

Equation 8 states that the minimum number of buses needed to warrant a bus lane must be equal to or greater than the number of automobiles in the off-peak direction and must be factored by the ratio of car-to-bus passenger occupancies for the off-peak and peak directions respectively. This number is then further modified to reflect the expected change in travel time for the buses in their own reserved lane as well as the travel times for automobiles with less highway capacity. Equation 8 ensures that the total person-delay will be less after bus lane implementation than it was before.

Speed-Delay Concept

In applying Eq. 8 and solving for B_1, the independent variables must be assumed or determined. These independent variables include estimates of the changes in automobile and bus travel times that are due to the contraflow bus lane. Changes in operating speeds (and, therefore, travel times) are assumed to be a function of traffic volume-capacity ratios only. The approximate relationship expressing this is

$$\text{Speed}_i = \text{Speed}_o - A\frac{V_i}{C} \quad (9)$$

where

Speed_i = speed at designated volume,
Speed_o = maximum highway speed,
A = calibration constant,
V_i = highway traffic volume, and
C = capacity of highway.

As a point of departure, the relation between speed and volume capacity (V/C) ratios was established (1, Fig. 9-1). The application of these ratio curves provided a basis for Tables 3, 4, 5, and 6 and calibration of the model (Eq. 8).

Model Results

The approximate minimum bus volumes that are required to warrant (from a person-delay standpoint) installation of a contraflow bus lane are given in Table 2. These bus volumes were estimated from Eq. 8. Basically, Table 2 defines the domain of practical application—hourly bus volumes between 40 and 200 buses—that most urban areas will be dealing with.

The data are also shown in Figure 1. The curves indicate the traffic volumes needed to warrant 40, 60, 80, 100, and 150 buses in a reserved lane; they are derived from Table 2. Because the results are related to travel time (speed) and volume, the number of buses required to minimize person-delay is nonlinear. Generally, as traffic becomes

Figure 1. Contraflow bus lane concept, six-lane freeway.

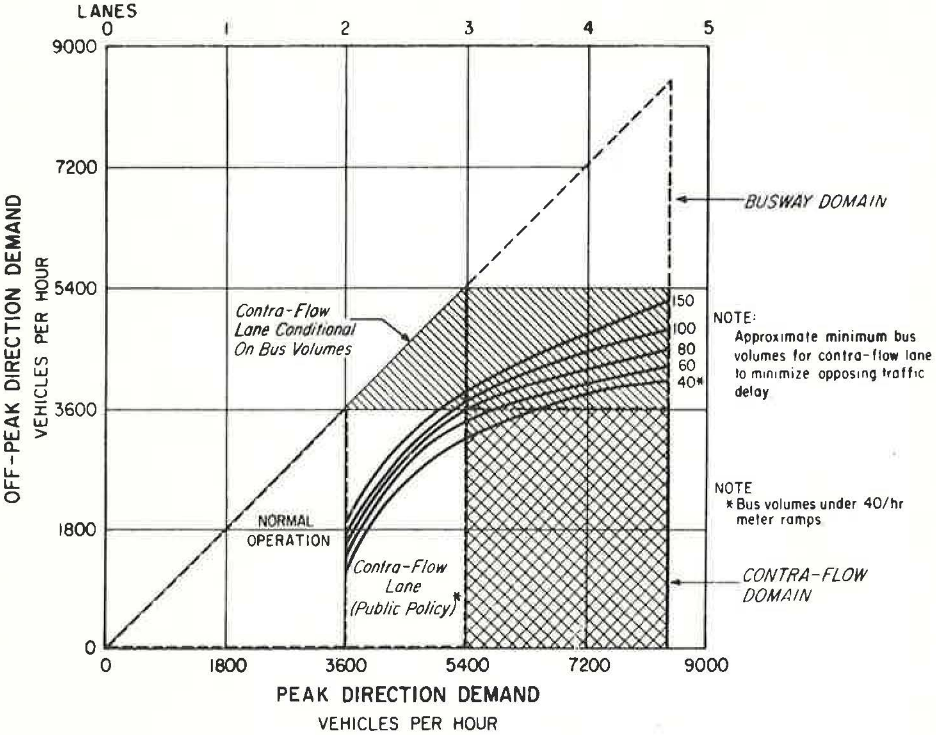

Table 3. Speed-volume relation, peak direction.

Demand (volume/ lane/hour)	$\frac{V}{C}$	Assumed Speed (mph)	Travel Time (min/mile)
300	0.17	56	1.07
400	0.22	55	1.10
500	0.28	54	1.12
600	0.33	52	1.15
700	0.39	51	1.18
800	0.44	50	1.21
900	0.50	48	1.25
1,000	0.56	47	1.28
1,100	0.61	46	1.32
1,200	0.67	44	1.37
1,300	0.72	43	1.43
1,400	0.78	41	1.46
1,500	0.83	40	1.50
1,600	0.89	37	1.58
1,700	0.94	34	1.69
1,800	1.00	30	2.00
1,900	1.06	24	2.40
2,000	1.11	22	2.76
2,100	1.17	19	3.16
2,200	1.22	17	3.43
2,300	1.28	15	4.00
2,400	1.33	14	4.29
2,500	1.39	12	5.00
2,600	1.44	11	5.45
2,700	1.50	09	6.67

Note: C = 1,800.

Table 4. Bus travel time-savings, peak direction, min/mile.

Demand (volume/hour in peak direction)	$\frac{V}{C}$	General Traffic (min/mile)	Bus Travel Time-Savings, Δt_1 (min/mile)
3,600	0.67	1.37	0.04
3,900	0.72	1.43	0.10
4,200	0.78	1.46	0.13
4,500	0.83	1.50	0.17
4,800	0.89	1.58	0.25
5,100	0.94	1.69	0.36
5,400	1.00	2.00	0.67
5,700	1.06	2.40	1.07
6,000	1.11	2.76	1.43
6,300	1.17	3.16	1.83
6,600	1.22	3.43	2.10
6,900	1.28	4.00	2.67
7,200	1.33	4.29	2.96
7,500	1.39	5.00	3.67
7,800	1.44	5.45	4.12
8,100	1.50	6.67	5.23

Notes: Maximum bus operating speed is 45 mph or 1.33 min/mile. Thus, where general traffic speeds are 1.37 min/mile, the savings from the bus lane are (1.37 - 1.33) or 0.04 min/mile. C = 5,400.

Table 5. Off-peak direction speed changes from lane reduction.

Total Volume, Off-Peak Direction	Without Lane Removed		With Lane Removed		Travel Time Loss, Δt_2
	$\frac{V}{C}$ (3 lanes)	t_2 (min/mile)	$\frac{V}{C}$ (2 lanes)	t_4 (min/mile)	
900	0.17	1.07	0.25	1.12	0.05
1,000	0.19	1.07	0.28	1.12	0.05
1,100	0.20	1.08	0.31	1.13	0.05
1,200	0.22	1.10	0.33	1.15	0.05
1,300	0.24	1.11	0.36	1.17	0.06
1,400	0.26	1.12	0.39	1.18	0.06
1,500	0.28	1.12	0.42	1.20	0.08
1,600	0.30	1.13	0.44	1.21	0.08
1,700	0.31	1.13	0.47	1.22	0.09
1,800	0.33	1.15	0.50	1.25	0.10
1,900	0.35	1.15	0.53	1.26	0.11
2,000	0.37	1.16	0.56	1.28	0.12
2,100	0.39	1.18	0.58	1.31	0.13
2,200	0.41	1.18	0.61	1.32	0.14
2,300	0.43	1.20	0.64	1.35	0.15
2,400	0.44	1.21	0.67	1.37	0.16
2,500	0.46	1.22	0.69	1.40	0.18
2,600	0.48	1.25	0.72	1.43	0.18
2,700	0.50	1.25	0.75	1.43	0.18
2,800	0.52	1.26	0.78	1.46	0.20
2,900	0.54	1.28	0.81	1.48	0.20
3,000	0.56	1.28	0.83	1.50	0.22
3,100	0.57	1.30	0.86	1.56	0.26
3,200	0.59	1.30	0.89	1.58	0.28
3,300	0.61	1.32	0.92	1.60	0.28
3,400	0.63	1.33	0.94	1.69	0.36
3,500	0.65	1.36	0.97	1.76	0.40
3,600	0.67	1.37	1.00	2.00	0.63
3,700	0.69	1.40	1.03	2.31	0.91
3,800	0.70	1.40	1.06	2.40	1.00
3,900	0.72	1.43	1.08	2.50	1.07
4,000	0.74	1.43	1.11	2.76	1.33
4,100	0.76	1.46	1.14	2.93	1.47
4,200	0.78	1.46	1.17	3.16	1.70
4,300	0.80	1.47	1.19	3.33	1.86
4,400	0.81	1.48	1.22	3.43	1.95
4,500	0.83	1.50	1.25	3.75	2.25

Table 6. Travel time change ratios.

Total Peak Direction (volume per hour)	Δt_1	Total Off-Peak Direction (volume per hour) and Δt_2												
		900, 0.05	1,200, 0.06	1,500, 0.08	1,800, 0.10	2,100, 0.13	2,400, 0.16	2,700, 0.18	3,000, 0.22	3,300, 0.28	3,600, 0.63	3,900, 1.07	4,200, 1.70	4,500, 2.25
3,600	0.04	1.25	1.50	2.00	2.50	3.25	4.00	4.50	5.50	7.00	15.75	26.75	42.50	56.25
3,900	0.10	0.50	0.60	0.80	1.00	1.30	1.60	1.80	2.20	2.80	6.30	10.70	17.00	22.50
4,200	0.13	0.38	0.46	0.62	0.77	1.00	1.23	1.38	1.69	2.15	4.85	8.23	13.08	17.31
4,500	0.17	0.29	0.35	0.47	0.59	0.76	0.94	1.06	1.29	1.65	3.71	6.29	10.00	13.24
4,800	0.25	0.20	0.24	0.32	0.40	0.52	0.64	0.72	0.88	1.12	2.52	4.28	6.80	9.00
5,100	0.36	0.14	0.17	0.22	0.28	0.36	0.44	0.50	0.61	0.78	1.75	2.97	4.72	6.25
5,400	0.67	0.07	0.09	0.12	0.15	0.19	0.24	0.27	0.33	0.42	0.94	1.60	2.54	3.36
6,300	1.83	0.03	0.03	0.04	0.05	0.07	0.09	0.10	0.12	0.15	0.34	0.58	0.93	1.23
7,200	2.96	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.09	0.21	0.36	0.57	0.76
8,100	5.34	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.12	0.20	0.32	0.42

Note: Off-peak direction volume = 2,400, Δt_2 = 0.16; peak direction volume = 5,400, Δt_1 = 0.67; ratio = 0.16/0.67 = 0.24.

balanced in both directions, a greater number of buses are required to warrant a contraflow bus lane. As the flow of traffic becomes imbalanced, fewer buses are needed. Figure 1 shows that with a flow less than 3,600 vehicles per hour in the heavy direction, buses can continue to operate normally because their speeds will already be about 45 mph or more. With traffic heavy in both directions, it becomes desirable to construct or use a separate busway.

The basic steps and relationships required to establish Table 2 and Figure 1 are given in Tables 3, 4, 5, and 6. Table 3 shows the relationship between speed and traffic volume. It shows a nonlinear decrease in speed (increase in travel time) as vehicle demand increases and approaches or exceeds the facility's capacity. Table 4, similar to Table 3, gives the expected changes in bus travel time (Δt_1) as a result of the exclusive bus lane. It assumes a maximum bus operating speed of 45 mph. Table 5 gives the vehicle travel time losses in the off-peak travel direction (Δt_2) resulting from the loss of one usable highway lane (designated for buses). It is assumed that travel by automobile in the peak direction is not changed because the removal of the buses to their own exclusive lane will not affect these vehicles. Table 6 gives the relation between Δt_1 and Δt_2 for various traffic volumes in the peak and off-peak travel directions. This relation is then used in Eq. 8 with assumed automobile and bus occupancies and traffic volume in the off-peak direction to establish the required number of buses to warrant an exclusive bus lane.

SUMMARY

Contraflow bus lanes should generally produce time-savings to bus passengers that exceed the time losses imposed on traffic in the opposite direction. Meeting this broad criterion calls for an increase in the minimum number of peak-hour buses as traffic in the off-peak direction rises and approaches (or exceeds) capacity. The model quantifies the number of buses required for a contraflow bus lane. As such, it represents a tool that urban and transportation planners may use in determining the feasibility for contraflow bus operations on urban freeways. The model should be tested under vehicle load factors, on traffic lanes (freeway width), and with volume-capacity speed functions to provide a more complete guide for practical applications. This information could then provide inputs to determine the model's sensitivity and range of application.

The procedure demonstrated one rational procedure for implementing an exclusive bus lane and assessing its potential benefits. Other policy factors should be considered in establishing bus lanes on freeways. The use of exclusive bus lanes is particularly timely in light of regulations that are being established to meet air quality and energy conservation needs.

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