OPERATIONAL ANALYSES OF FREEWAY MOVING-MERGE SYSTEMS

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Experimental moving-merge control systems were tested in Woburn, Massachusetts. This paper presents findings relative to how ramp drivers used the system and what they thought of the moving-merge concept. A green-band and a pacer system were evaluated. Analyses relative to system effectiveness and use included driver responses obtained from questionnaires, the extent to which ramp drivers used ramp-side displays, and the effect moving-merge systems had on traffic operations. Questionnaire responses indicated that drivers approved of the moving-merge concept and 70 percent found the systems understandable. This statistic was independent of driver age and type of system. Of the drivers who used both systems, 70 percent stated that the green-band system helped most in merging and was easier to understand and use. Analyses were developed to evaluate driver use of the ramp-side, displayed information. These analyses showed that the probability of drivers' using a lighted display downstream of the ramp was more significant for the green-band drivers who had been conditioned to having a lighted display upstream of the ramp. According to the average number of displays viewed per driver, the green-band system was used more consistently than was the pacer system. The mean relative velocity between green bands and ramp vehicles was significantly lower for drivers using the bands. Analyses were used to evaluate traffic operations within the freeway right lane and acceleration lane. Drivers using the systems improved their merge position without disrupting freeway traffic.

•RAMP-CONTROL systems, many types of which have been in use since 1960, control the flow of vehicles onto a freeway to maintain freeway operations at an acceptable level of service. Ramp-control systems can be used on individual on-ramps or on sequences of on-ramps. The most common types of ramp control are total-ramp-closure, pretimed, gap-acceptance, and traffic-responsive systems. Another type of ramp control is the moving-merge system, which uses gap-acceptance control and information display. The displayed information helps the ramp driver identify gaps and merge easily into the freeway flow even when the view of the right lane is restricted. The moving-merge concept was first considered and tested in 1968 by simulated freeway tests on an abandoned airport (1, p. 232). These prototype tests showed that (a) ramp drivers could follow the displayed gap information presented on the ramp, (b) drivers were placed in a successful merge position 70 percent of the time, (c) the moving-merge concept was feasible, and (d) further development was warranted.

After these tests, the Federal Highway Administration contracted to develop functional requirements, control logic, and design specifications for 2 types of moving-merge systems. On the basis of the design specifications, each system was fabricated, assembled, and operated at a single on-ramp in Woburn, Massachusetts (2, pp. 4-11; 3). The Woburn site was selected for the first public tests because it has a long, 700-ft (213-m) acceleration lane. This long acceleration lane offered a safety advantage by providing additional space for ramp vehicle maneuvering.

The design of both merge-control systems was based on gap-acceptance control. The green-band system represented right-lane gaps as moving green bands on a ramp-side display. The pacer system used a green pacer light to lead ramp drivers to the merge area. The green-band and pacer systems are shown in Figures 1 and 2. The green-band system used open-loop control in which trajectories of the green bands were independent of the behavior of the ramp vehicles. The pacer system, however, used closed-loop control, and the individual pacer-light trajectories were based on the movement of both the freeway gap and the ramp vehicle.

The basic purposes of the Woburn evaluation were to determine whether the development and operation of moving-merge systems would be technically feasible, how ramp drivers would react to the moving-merge concept, and whether ramp drivers would use the system.

SYSTEM DESCRIPTIONS

Experimental field tests were performed on each system in 1970 at Routes 38 and 128 in Woburn. For both systems a Raytheon 703 minicomputer with 12,000 words of core storage was used for surveillance, decision-making, and system control. Peripheral equipment included a high-speed, paper-tape unit for reading operational programs and a magnetic tape unit for recording real-time data. For surveillance and evaluation, 7 sets of inductive loop sensors 200 ft (60.8 m) apart were used to monitor vehicle movement in the freeway's right lane; 10 sets of sensors 64 ft (19.2 m) apart were used on the ramp. Five 50-ft (15.1-m) presence sensors were installed in the acceleration lane to monitor the presence of stopped vehicles.

Green-Band System

The green-band system operated in (a) moving, (b) stopped-gap-acceptance (SG), and (c) stopped-metered (SM) states. In the Woburn tests, the state in which the green-band system operated was determined by the average 3-min speed in the freeway's right lane. When the average 3-min speed was greater than 35 mph (56 km/h), the system operated in the moving state.

In the moving state, the computer determined the location of acceptable gaps in the right lane as each vehicle crossed an inductive-loop detector in the freeway. Representations of these acceptable gaps were then displayed as moving green bands on the ramp-side display unit. When the ramp driver stayed adjacent to a green band as it moved at a constant speed along the ramp-side display, he or she would arrive in the merge area within an acceptable gap. The moving green bands lengthened, shortened, or disappeared depending on how the right-lane gaps varied.

When the average 3-min speed fell below 35 mph (56 km/h), the green-band system operated in either the SG or SM state. The SG state was similar to conventional, pretimed, ramp-control systems except that in it the traffic signal released a waiting ramp vehicle with a green indication and a 32-ft (9.7-m) accelerating green band on the

Figure 1. Green-band system.

Figure 2. Pacer system.

ramp-side display when an acceptable gap was available. The short green band would lead the ramp vehicle to the acceptable gap in the merge area. If no acceptable gap were found within a predetermined time period, the waiting vehicle would be released but no accelerating green band would be used. In the SM state, all vehicles were metered individually without an accelerating green band.

Pacer System

The major difference between the pacer system and the green-band system was that in the pacer system the speed and location of all ramp vehicles were continuously monitored as they moved along the ramp. As in the green-band system, the computer maintained a list of right-lane vehicle arrivals in the merge area. When a vehicle entered the ramp, the computer calculated its expected time of arrival in the merge area and searched the freeway list for a gap large enough for the ramp vehicle. When the computer matched a ramp vehicle with an acceptable gap, an individual pacer light was displayed to the driver. The pacer light, positioned about 1 car length in front of the driver, guided the ramp driver to the merge area so that both the ramp driver and the freeway gap arrived at the same time. More than 1 ramp vehicle could be accommodated simultaneously. The movement of each pacer light was accelerated or decelerated by the computer according to the relative relationship between the ramp vehicle and its respective merge gap. For the Woburn tests, ramp vehicles that lost an acceptable gap or those that did not have an acceptable gap continued along the ramp without a pacer light.

RAMP DRIVER RESPONSES

The green-band and pacer merge-control systems were operated from 7:00 a.m. to 7:00 p.m. for approximately 8 weeks each. The pacer system operated during May and June 1970, and the green-band system operated during September and October 1970. Before the start of each operational period, local newspapers described how the systems functioned and how drivers should use the information. In addition, brochures describing how the systems were to be used were distributed at the on-ramp for several days before each phase.

The success or failure of traffic aids such as the green-band and pacer merge-control systems depends on drivers. To appraise individual driver reactions to the merge-control systems, questionnaires were distributed to the ramp drivers after each system had been in use for 8 weeks. The questionnaires were distributed at 3 locations near the on-ramp entrance in the morning, at midday, and in the afternoon. The morning period represented the peak freeway and ramp flows. The off-peak flows occurred during the midday and afternoon periods. One thousand five hundred and twenty green-band system questionnaires and 1,582 pacer system questionnaires were distributed. Nineteen percent of the green-band questionnaires and 25 percent of the pacer questionnaires were returned.

System Clarity

Table 1 was prepared to determine whether drivers responded differently, on the basis of type of system or driver age, to the question, "Was the entire merging control system clear and understandable?" With respect to driver age, the chi-square analysis shows that age is independent of type of merge-control system and system clarity. The degrees of freedom (df) for independence of age, A, systems, S, and clarity, C, is 10. The df was obtained by subtracting $(A - 1) + (S - 1) + (C - 1)$ from $(A \times S \times C) - 1$.

In addition to examining the independence of age, type of merge-control system, and system clarity, we examined other interactions. The chi-square test can be used to calculate the individual interactions. But, as Kullback (5, pp. 12-14) has shown, information theory also can be easily employed for tests of contingency tables; the information statistic is distributed asymptotically as is chi-square, and it has additive and convex properties that make its use convenient. Therefore, information statistics for each of the interactions are given in Table 2. In addition, the information statistics for all of the main effects as well as a comparative chi-square statistic for each main effect and interaction are included in Table 2.

As shown by the Table 2 interactions, neither the information statistic nor the chi-square test rejected independence among age, system clarity, or type of merge-control system. Consequently, there was no degradation in system clarity because of driver age or type of merge-control system. Also the only main-effect component of interest is system clarity; about 70 percent of the drivers found the system clear and understandable.

System Location

Merge control is intended to be used at substandard ramps where drivers experience difficulty in merging and where reconstruction of the merge area is not feasible or is too costly.

The data of Table 3 were used to test the independence of the observed response for the 2 merge concepts. Respondents were asked in the questionnaires whether they thought the systems were needed at most ramps, needed at poorly designed ramps only, or not needed. As indicated in Table 4, the chi-square test did not reject the hypothesis of independence between the 2 data sets. This suggests that the drivers' opinions on where merge control was needed were not significantly affected by the type of merge system considered. Furthermore, about half of the drivers stated that the systems were needed at poorly designed ramps only.

System Difficulty

In order to evaluate the drivers' views of their experiences in using the merging systems, 2 questions on the degree of difficulty in driving beside the display lights were asked. The first concerned their first use of the systems and the second concerned their use after gaining experience. Degrees of difficulty were difficult, slightly difficult, and easy. The responses for the green-band and pacer merging systems are given in Table 4.

A test was made to determine whether acquaintance with the system was independent of type of merge system and degree of difficulty. As shown by Table 4, the hypothesis of independence was rejected, implying that the observed percentages at each level were not uniform for each system from one time to another. Based on this finding, the statistical significance of both the main effects and interactions was computed by using information theory. Results are given in Table 5.

Before reviewing the components of Table 6, one should understand that no restriction was placed on the number of green-band and pacer questionnaires analyzed. The number analyzed was solely a function of the number of usable questionnaires returned for each system. Consequently, no real importance can be associated with the significant main effects for the type of system, S, or for acquaintance with system use, T; similarly, no real importance can be associated with the significant interaction of T × S. The remaining significant components shown in Table 6 now can be discussed in greater detail.

For the main effect on level of difficulty, D, the information statistic clearly shows that the distribution of responses at each level, combined over systems, was highly significant; approximately 65 percent of the drivers answered that it was easy to drive beside the moving-display lights.

The interaction of acquaintance with the system and level of difficulty, T × D, was significant. This implies that the drivers detected a difference in how difficult it was to drive beside the moving-display lights for the first time as compared to how difficult it was after they had gained experience. It can also be shown that the same conclusion

Table 1. Effect of driver age on system clarity.

	Response[a]				
	Yes		No		
Age (years)	Number	Percent	Number	Percent	Sample
Green-Band System					
Under 22	13	61.9	8	38.1	21
22 to 30	47	62.7	28	37.3	75
31 to 55	105	71.4	42	28.6	147
Over 55	11	68.8	5	31.2	16
Total	176	68.0	83	32.0	259
Pacer System					
Under 22	18	78.3	5	21.7	23
22 to 30	49	64.5	27	35.5	76
31 to 55	111	74.0	39	26.0	150
Over 55	11	73.3	4	26.7	15
Total	189	71.6	75	28.4	264

Note: $\chi^2 = 5.89$, $\chi^2_{0.05,\,10} = 18.3$.

[a]The question was, "Was the entire merging control system clear and understandable?"

Table 2. Main effect and interaction components of Table 1.

Component	Information	χ^2	Degrees of Freedom	$\chi^2_{0.05,\,df}$
Main effects				
A	345.748	348.182	3	7.81
C	84.215	81.930	1	3.84
S	0.045	0.047	1	3.84
Interactions				
A × C	3.940	4.010	3	7.81
A × S	0.112	0.123	3	7.81
C × S	0.821	0.820	1	3.84
A × C × S	0.976	0.977	3	7.81
All effects and interactions	435.857	436.089	15	25.00

Table 3. Where merge control is needed.

	Suggested Location						
	Most Ramps		Poorly Designed Ramps Only		Not Needed		
System	Number	Percent	Number	Percent	Number	Percent	Sample Size
Green band	62	24.8	115	46.0	73	29.2	250
Pacer	91	26.2	169	48.7	87	25.1	347
Total	153	25.6	284	47.5	160	26.9	597

Note: $\chi^2 = 1.26$, $\chi^2_{0.05,\,2} = 5.99$.

Table 4. Degree of difficulty of driving beside moving-display lights.

	Level of Difficulty						
	Difficult		Slightly Difficult		Easy		
Acquaintance With System	Number	Percent	Number	Percent	Number	Percent	Sample Size
Green band							
First	25	16.0	59	37.8	72	46.2	156
Experienced	8	7.1	34	30.1	71	62.8	113
Total	33	12.3	93	34.6	143	53.1	269
Pacer							
First	23	6.8	121	36.0	192	57.2	336
Experienced	16	4.9	65	20.1	243	75.0	324
Total	39	5.9	186	28.2	435	65.9	660

Note: $\chi^2 = 58.61$, $\chi^2_{0.05,\,7} = 14.1$.

is valid when the green-band and pacer responses are considered individually. This is supported by the fact that the information statistics for the individual green-band and pacer analyses were 9.10 and 24.16 respectively, which, when compared to $X^2_{0.05}$ with 2 df, rejects the hypothesis of independence. Drivers had less difficulty in using the systems after they had gained experience.

The information statistic also showed that a significant interaction for D × S was present. Closer review of Table 4 indicates that the overall ranking of level of difficulty in driving beside the moving display was higher for the pacer system than for the green-band system. This means that drivers found it easier to drive beside the display in the pacer system. For example, nearly 15 percent more pacer responses were marked easy. This is probably because the pacer system updated the movement of the pacer light according to how the ramp driver was moving along the ramp.

Preferred System

On the green-band questionnaire, those drivers who had used both systems were asked the questions given in Table 6 to determine which system was preferred. Table 6 determines whether the number of individual preferences for both of the 2 systems were homogeneous across each query. As given in Table 6, the chi-square test failed to reject homogeneity among the 3 system queries. This can also be shown by the normal approximation of the binomial test that preference was for the green-band system and that the proportion, p, of drivers having a preference for the green-band system can be expressed as $Pr(0.67 < p < 0.77) = 0.95$. Approximately 70 percent responded that the green-band system helped most in merging and was easier to understand and to use.

USE OF RAMP-SIDE DISPLAY

Two approaches were developed to determine how drivers used the ramp-side displays. One approach considered the composite use of the display by all ramp drivers regardless of whether they had a choice in using the display information. The second approach was more selective in that it considered only those drivers who could choose whether to use the display information.

Composite Measures of Display Use

The measures described here were composites in the sense that they included all drivers who used the ramp regardless of the chance they had to use the moving-merge information. Thus the composite measures can be used to compare the effectiveness of the 2 systems with respect to each other as well as to no system.

Conditional Lighted Display Probabilities

The driver display, located directly beside the vehicle, was either lighted or unlighted when a driver crossed a given set of ramp detectors. A lighted display indicated that the driver was under control and was expected to arrive in the merge area at the same time that an acceptable gap in traffic would be available on the freeway. An unlighted display indicated that the driver was not expected to arrive in the merge area at the same time as an acceptable gap in traffic. The conditional probability of a driver's having a lighted display at sensor location j (S_j) if there were one at sensor location i (S_i) is expressed as

$$p(j|i) = \frac{p(i,j)}{p(i)}, \quad (j > i)$$

Table 5. Main effect and interaction components for Table 4.

Component	Information	Degrees of Freedom	$\chi^2_{0.05,\,df}$
Main effects			
Acquaintance with system, T	3.26	1	3.84
Level of difficulty, D	453.17	2	5.99
System, S	169.80	1	3.84
Interactions			
T × D	33.09	2	5.99
T × S	3.86	1	3.84
D × S	16.83	2	5.99
T × D × S	0.18	2	5.99
All effects and interactions	680.19	11	19.70

Table 6. Driver preferences.

Question	Green Band		Pacer		Sample Size
	Number	Percent	Number	Percent	
Which system was easier to understand?	78	70.3	33	29.7	111
Which system was easier to use?	91	72.2	35	27.8	126
Which system helped most in merging?	73	73.7	26	26.3	99
Total	242	72.0	94	28.0	336

Note: $\chi^2 = 0.32$. $\chi^2_{0.05,\,2} = 5.99$.

Table 7. Model notation.

System	Notation	Probability
Green band		
On	x_1	p_{11}
Off	x_2	p_{12}
Total	N_1	
Pacer		
On	y_1	p_{21}
Off	y_2	p_{22}
Total	N_2	
Both		
On	$x_1 + y_1$	p_1
Off	$x_2 + y_2$	p_2
Total	$N_1 + N_2$	

Table 8. Green-band and pacer system comparisons of conditional probability of a lighted display at S_j given a lighted display at S_i.

System	S_i	$S_{j=1}$			$S_{j=2}$			$S_{j=3}$			$S_{j=4}$			$S_{j=5}$		
		Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]
Green band	1	71	1.00	0	58	0.82	6.35[b]	57	0.80	2.71	53	0.75	1.78	53	0.75	4.84[b]
Pacer	1	292	1.00	0	268	0.92	6.35[b]	206	0.71	2.71	194	0.66	1.78	177	0.61	4.84[b]
Green band	2				85	1.00	0	69	0.81	5.09[b]	62	0.73	1.06	63	0.74	5.16[b]
Pacer	2				353	1.00	0	243	0.69	5.09[b]	237	0.67	1.06	215	0.61	5.16[b]
Green band	3							89	1.00	0	71	0.80	0.72	68	0.76	2.42
Pacer	3							301	1.00	0	227	0.75	0.72	204	0.68	2.42
Green band	4										96	1.00	0	77	0.80	2.65
Pacer	4										309	1.00	0	222	0.72	2.65
Green band	5													104	1.00	0
Pacer	5													287	1.00	0

System	S_i	$S_{j=6}$			$S_{j=7}$			$S_{j=8}$			$S_{j=9}$		
		Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]	Volume	p(j|i)	$2\hat{I}$[a]
Green band	1	50	0.70	3.76	50	0.70	4.80[b]	51	0.72	7.34[b]	50	0.70	6.21[b]
Pacer	1	169	0.58	3.76	164	0.56	4.80[b]	158	0.54	7.34[b]	158	0.54	6.21[b]
Green band	2	59	0.69	4.42[b]	60	0.71	5.95[b]	60	0.71	7.11[b]	58	0.68	6.02[b]
Pacer	2	201	0.57	4.42[b]	198	0.56	5.95[b]	193	0.55	7.11[b]	189	0.54	6.02[b]
Green band	3	63	0.71	2.40	63	0.71	2.94	65	0.73	6.17[b]	62	0.70	5.20[b]
Pacer	3	186	0.62	2.40	183	0.61	2.94	176	0.58	6.17[b]	169	0.56	5.20[b]
Green band	4	72	0.75	4.38	67	0.70	1.86	66	0.69	3.19	63	0.66	1.52
Pacer	4	196	0.63	4.38	192	0.62	1.86	181	0.59	3.19	181	0.59	1.52
Green band	5	88	0.85	4.94	83	0.80	4.95[b]	81	0.78	5.73[b]	76	0.73	3.40
Pacer	5	212	0.74	4.94	196	0.68	4.95[b]	187	0.65	5.73[b]	181	0.63	3.40
Green band	6	107	1.00	0	87	0.81	1.27	84	0.79	2.14	82	0.77	2.66
Pacer	6	270	1.00	0	205	0.76	1.27	192	0.71	2.14	184	0.68	2.66
Green band	7				108	1.00	0	94	0.87	5.94[b]	91	0.84	7.25[b]
Pacer	7				272	1.00	0	206	0.76	5.94[b]	193	0.71	7.25[b]
Green band	8							110	1.00	0	103	0.94	16.46[b]
Pacer	8							270	1.00	0	204	0.76	16.46[b]
Green band	9										114	1.00	0
Pacer	9										248	1.00	0

[a]This statistic obeys the approximate χ^2 distribution with 1 df.

[b]Significantly different at the 0.05 level.

This analysis uses the concept of conditional probability to determine whether use of the driver display differed for the green band and pacer systems. For the ideal situation, if a ramp driver were always under control and had a display at detector i, then the probability $p(j|i)$ that he or she would be under control at detector j always would be 1.00.

In the resulting model for each i,j combination $j > i$ [with underlying $p(j|i)$], 2 independent random samples, N_1 and N_2, corresponding to 2 system conditions, were obtained. Each of these samples thus can be regarded as a set of independent observations from a binomial distribution. The samples N_1 and N_2 were for the green-band and pacer systems respectively; a complete notational description is given in Table 7.

Each observation in the set of N_1 observations is assumed to have a probability p_{11} (that the ramp driver had an "on" display at location i and an "on" display at location j). Thus, in this model, $p_{11} \equiv p_1(j|i)$ and $p_{12} \equiv 1 - p_{11}$. Similarly for set N observations, $p_{21} \equiv p_2(j|i) \equiv 1 - p_{22}$. We wish now to determine whether $p_{11} = p_{12}$. The null hypothesis to be tested is that samples $x = (x_1, x_2)$ and $y = (y_1, y_2)$ are from the same overall population, $p = (p_1, p_2)$. Kullback (5, p. 128) analyzed this type of problem in terms of the information statistic 2I for the more general case involving c data sets. Kullback showed that 2I can be approximated by

$$2I = \frac{1}{N_1N_2} \sum_{k=1}^{c} \frac{(N_2x_k - N_1y_k)^2}{x_k + y_k}$$

with c - 1 df.

Table 8 gives the data and set of analyses for each location corresponding to a merge volume of 1,750 vehicles per hour (vph). For appropriate interpretation, it must be realized that the 2I statistics, calculated for each value of i, are not independent. That is, if the value of 2I at $j = 2$ for $i = 1$ is low, one would expect that a similar result would prevail at $j = 3$ for $i = 1$ because of the proximity of these locations. Even if the 2I statistics were independent, one would anticipate under the null hypothesis that 5 percent of a large quantity would be higher than the critical 0.95 value. Twenty 2I statistics for 1,750-vph merge volume and twenty-four 2I statistics for 1,000-vph merge volume exceeded the critical 0.95 value of chi-square. Because numbers as large as these are quite unlikely, the green-band and pacer conditional probabilities are not homogeneous. Studied interpretation of the results can show that the probability of a driver's having a lighted display at location j was higher for the green-band system than for the pacer system if a lighted display was at i.

In examining the difference in these results, one should remember that the pacer system was a closed-loop system designed to lead and keep ramp drivers within an acceptable gap. If the pacer concept had been truly effective, the $p(j|i)$ would have been greater for the pacer system than for the green-band system. However, the findings suggest otherwise. The results of the conditional probability studies suggest that drivers tended to stay within an acceptable gap more often with the green-band system than with the pacer system. For the pacer system, only 1 pacer light was displayed per driver at any time; consequently, drivers did not have as extensive a visual impression of the size of the gap as they had with the green-band system. The limited information provided from the pacer light might be the key explanation for the difference in these results.

Average Number of Lighted Displays per Driver

A ramp driver who approached the beginning of the driver display with the merge-control system in operation may or may not have had a lighted display. If a lighted display was at each detector along the length of the ramp, he or she used 1 uninterrupted green band or pacer to drive in relation to only 1 acceptable freeway gap. If, on the other hand, the gap closed and was no longer acceptable, the lighted display was stopped by the system somewhere along the ramp. When this occurred the ramp driver might have obtained another green band or pacer for a different acceptable gap at some point further along on the ramp. Thus, a ramp user may drive beside a succession of k uninterrupted moving displays ($k = 0, 1, 2, \ldots$) while moving down the ramp to the merge area. No display light signified that the computer was unable to find an acceptable gap for the driver.

When the freeway merge volume was zero, the average number of continuous green bands or pacers that would be viewed by the ramp driver would be 1 because, at this volume, the driver would have an uninterrupted lighted display throughout the length of the ramp. At the other extreme, as the freeway merge volume approached capacity (2,000 vph), the average number of green bands or pacers that would be displayed to a ramp vehicle would approach zero. At freeway merge volumes between zero and capacity, the average number of green bands or pacers used by a ramp driver varied depending on (a) the probability of a green band or pacer and (b) how drivers used the 2 systems.

To determine whether there was any difference in how drivers used the ramp-side information for the 2 systems, an evaluation was made based on the comparison of 2 independent data sets. This method hypothesizes that the average number of lighted displays per driver, $\bar{k}$, is the same for both the green-band and pacer systems. The comparison required the use of least squares regression models. The following models were used:

$$y = 1 + a_1 m + a_2 m^2$$

$$y^* = 1 + b_1 m + b_2 m^2$$

where

y = average number of continuous displays per driver for the green-band system,
y^* = average number of continuous displays per driver for the pacer system,
$a = (a_1, a_2)$, a least squares estimate of the model parameter,
$b = (b_1, b_2)$, a least squares estimate of the model parameter, and
m = merge volume in 100 vehicles per hour (when $m = 0$, $y = y^* = 1$).

Individual parameter values are given in Table 9.

The comparison also required that a least squares estimate [$c = (c_1, c_2)$] be determined for the combined green-band and pacer sets of data. After all parameters were determined, an F-ratio was computed. The result of this analysis is given in Table 10, and, based on the F-statistic obtained, the above hypothesis was rejected at the 0.05 level of significance. Thus it can be inferred that, because $\bar{k}$ was less for the green-band drivers (1.3) than it was for the pacer drivers (1.5), the green-band display was used more consistently.

Selective Measures of Driver Display Usage

Because the selective measures to be described apply to either type of merge-control system and because future installations probably will be green-band systems, the analyses in this section have been restricted to the green-band system.

Some ramp drivers had no opportunity to use the moving green band as they moved down the ramp. This happened for 2 reasons. First, the driver arrived at the ramp entrance when there was no acceptable gap in traffic on the freeway and there never would be an acceptable gap no matter how much he or she accelerated. Second, the driver sometimes arrived at the ramp entrance when there was such a large gap in traffic that, no matter how much he or she accelerated or decelerated, he or she would

Table 9. Model parameters.

System	Data Set	Parameter 1	Parameter 2
Green band	On	0.0660	-0.00290
	Off	0.0606	-0.00256
Pacer	On	0.0690	-0.00221
	Off	0.0651	-0.00185

Table 10. Differences in display use measured by average number of lighted displays per driver for drivers having at least 1 display.

System	Data Set (i)	Data Points (N_i)	Sum of Squares[a] Regression (RSS_i)	Total (TSS_i)	Differences (R_D)	Error (ESS)	F-Ratio[b] [$F_{0.05,(2,df)}$]
Green band	1	7	12.310	12.314			
Pacer	2	11	22.810	22.893			
Both	1 and 2	18	35.120	35.207	0.100	0.087	8.046[c] (3.74)

[a] $R_D = RSS_1 + RSS_2 - RSS_{1\ and\ 2}$ and $ESS = TSS_{1\ and\ 2} - RSS_1 - RSS_2$.

[b] $df = N_{1\ and\ 2} - 4$ and F-ratio $= \frac{R_D/2}{ESS/df}$.

[c] Results differ significantly at the 0.05 level.

Figure 3. Green-band and vehicle time-space plot.

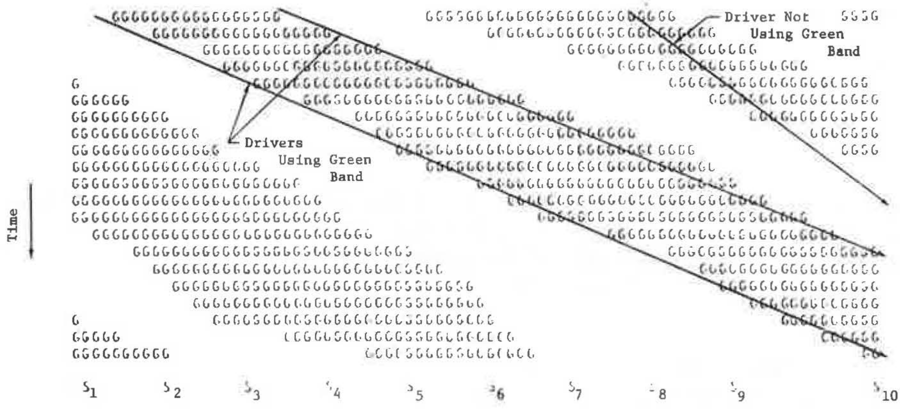

Table 11. Homogeneity of system-on and system-off, green-band, time-space data.

System Status	Driver Had No Chance To Get Out of Green Band: Number	Percent	Driver Had No Chance To Get Into Green Band: Number	Percent	Driver Had Chance to Use Green Band: Number	Percent
On	119	25.1	190	40.1	165	34.8
Off	89	29.3	119	39.1	96	31.6

Note: $\chi^2 = 1.82$, $\chi^2_{0.05,2} = 5.99$.

Table 12. Frequency comparison of drivers who may have used a green band as a function of system-on and system-off status.

System Status	Drivers Who Used Green Band: Number	Percent	Drivers Who Did Not Use Green Band: Number	Percent
On	111	67.3	54	32.7
Off	39	40.6	57	59.4

Note: $\chi^2 = 17.63$, $\chi^2_{0.05,2} = 3.84$.

always be beside the same gap. These types of cases were not studied so that a detailed study could be made of those vehicles that had a chance to use the displayed information.

The data for these analyses were obtained from green-band and vehicle time-space plots. Examples of typical time-space plots are shown in Figure 3. Each 8-ft (2.4-m) section of an individual green band is designated as G. The trajectories of the vehicles moving along the ramp are represented by a solid line. Vehicle trajectories on the time-space plots were examined to identify those for which the driver had a choice in the green-band display. A driver was considered to have had a choice in using a green band if he or she could have negotiated beside a green band before reaching the downstream end of the display without having to accelerate more than 4 ft/sec^2 (1.2 m/s^2) and if the following 2 conditions were not rejected:

1. The driver was able to see the moving green band in front of or beside his or her vehicle, and
2. The driver was not able to choose a green band because his or her movement was impeded by another ramp vehicle.

Probability Comparisons

The data for this analysis were obtained while the system software was operational but while the display was either on or off. With the data structured in this way, it was possible to compare how drivers used the ramp when the system was on to how they used it when it was off. In this analysis, merge volumes were sought that would permit a large number of green bands to be generated and observed; the merge volumes were between 900 and 1,500 vph.

Prior to the usage analysis, it was considered appropriate to determine whether the system-on and system-off data sets were similar with respect to the categories of drivers who (a) had no chance to get out of a breen band, (b) had no chance to get beside a green band, and (c) had a chance to use a green band. The chi-square test was used to evaluate the homogeneity of the system-on and system-off samples. As shown in Table 11, the chi-square test did not reject homogeneity for composition of the number of system-on and system-off observations for each of the 3 categories.

After finding that the 3 categories were similar, 2 individual evaluations were performed on the data set to determine the frequency with which drivers used green bands and how they used the green bands at the beginning and end of the display. First, a chi-square test was used to determine whether the degree of driver's use of the green-band system was homogeneous with the system's status. It is shown in Table 12 that the chi-square test rejected homogeneity between on and off. When the system was off, 41 percent of the drivers who had a chance to use the system performed in such a way that they appeared to use the undisplayed information, or, in other words, the system coincided with the driver's behavior. However, when the system was on, 67 percent of the drivers who had a chance to use the system did indeed use the displayed information. This clearly indicates that drivers were using the system. Second, an evaluation considered the display status when ramp drivers were at the beginning and at the end of the driver display for all those drivers who had a chance to use a green band. Transition matrices were developed for the system-on and system-off cases. These matrices are given in Table 13. Kullback, Kupperman, and Ku (6) have shown that information theory can be used to determine whether several realizations of matrices of transition probabilities are homogeneous. Their method was used for this evaluation and the results, given in Table 14, indicate that, for those drivers who had a chance to use a green band, the probability of their having a green band at the end of the driver display was improved significantly when the display was energized. The finding also suggests that some drivers were using the green-band system. The significance of this improvement is represented by the significant chi-square value of 6.2521 for the component effect of conditional homogeneity (k|j). The j homogeneity component of information merely indicated that the composition of states, disregarding the system-on and system-off conditions, was homogeneous and extraneous to our findings.

Table 13. Transition matrices for drivers who could have used the green-band display.

System Status	Beginning of Display (j)	End of Display (k): Not Beside Green Band, Number	Not Beside Green Band, Percent	Beside Green Band, Number	Beside Green Band, Percent
On	Not beside a green band	25	36	44	64
	Beside a green band	31	32	65	68
Off	Not beside a green band	21	43	28	57
	Beside a green band	25	53	22	47

Table 14. Homogeneity of transition matrices of Table 13.

Component	Information	Degrees of Freedom	$\chi^2_{0.05,\,df}$
j homogeneity	2.0814	1	3.84
Conditional homogeneity k|j	6.2521	2	5.99
j, k homogeneity	8.3335	3	7.81

Table 15. Green-band and relative velocity for drivers who used and drivers who did not use a green band.

Driver Use of Green Band	Sample Size	Cumulative Distribution (fps): -15	-10	-5	0	5	10	15	20	25
Drivers used green-band system	84	0.01	0.08	0.21	0.53	0.83	0.90	0.95	0.99	1.0
Drivers did not use green-band system	42	0.02	0.07	0.14	0.31	0.57	0.74	0.83	0.95	1.0

Note: 1 fps = 0.3 m/s.

Table 16. Gap-acceptance distributions.

Case	System Status	Display Status	Variance of Sample	Mean (sec)	Critical Gap[a] (sec)	Variance of Mean	Standard Normal Deviation
1	Off	—	10.431	3.584	3.5	0.250	—
2	On	Used	17.215	4.678	4.8	0.178	1.673[b]
3	On	Not used	10.946	3.795	3.6	0.233	0.304[c]

[a]Critical gap as determined by the Raff method.
[b]Mean is not significantly different from the mean of case 1 at the 0.10 level.
[c]Mean is significantly different from the mean of case 1 at the 0.10 level.

Table 17. System-off versus system-on leading headways.

System Status	Driver Usage of Band	Sample Size	Cumulative Distribution (sec): 1	2	3	4	5	6	7	8	>8
Off	—	125	0.088	0.376	0.544	0.688	0.752	0.800	0.864	0.904	1.00
On	Used	105	0.048	0.181	0.352	0.543	0.657	0.791	0.819	0.867	1.00

Table 18. Ratios of relative velocity to highway vehicle velocity for green band, system on, and green band, system off.

System Status	Sample Size	Cumulative Distribution (fps): -0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
Off	125	0.01	0.02	0.08	0.17	0.36	0.57	0.76	0.94	0.00	1.00
On, used	105	0.00	0.01	0.04	0.13	0.31	0.57	0.77	0.95	0.98	1.00

Note: 1 fps = 0.3 m/s.

Driver Tracking of a Moving Display

The task of following a moving display is analogous to following another vehicle. For vehicle-following cases, Montroll and Potts (7, p. 43) found that relative velocity between the 2 vehicles is a major influence on tracking. It thus can be hypothesized that the relative velocity between the green bands and the ramp vehicles would be less for drivers who used the moving display than for drivers who did not use the display. As used here, the relative velocity is the difference between the green-band and ramp-vehicle velocities. The analysis considers 2 subsets of drivers who had a chance to use green bands. One subset included the drivers who used green bands, and the other included those drivers who did not use a green band. Table 15 gives the cumulative distribution of the observed relative velocity for those drivers using and those not using a green band. The critical deviation would be 0.25, and the actual maximum absolute deviation between 2 distributions was 0.26 and occurred at a relative velocity of 5 fps (1.5 m/s). So, the distributions were significantly different at the 0.05 level. For this observed difference, the Kolmogorov-Smirnov 2-sample test would reject the hypothesis that the 2 samples came from the same distribution.

THE EFFECTS OF MOVING-MERGE SYSTEMS ON TRAFFIC OPERATIONS

The ability of ramp vehicles to merge into freeway traffic is affected by both geometric design elements and traffic operations at the site. The geometric design elements normally are fixed for a given site and cannot be altered except through reconstruction. Modest site alterations or improvements, including moving-merge systems, can affect traffic operations. The use of moving-merge systems to aid ramp drivers in merging into the freeway's right lane falls into this category. Thus evaluation of the effectiveness of moving-merge systems must involve the various traffic operational variables or measures that are featured.

Gap-Acceptance Characteristics

Drivers in a moving-merge system can time their arrival at the merge area to correspond with an acceptable gap. When there is no moving-merge system or when freeway traffic is hidden because of visual obstructions along the ramp, a driver would not have premerging information. Intuitively, then, one might expect that the mean gap accepted for merging would be different for the 2 cases. In fact, because the green-band system does not display small gaps (gaps of less than 2 sec), it would be expected that when drivers used the system the mean gap would be larger than when the system was not used because drivers would accept a greater percentage of small gaps. This section considers 1 case in which no green-band system was operated and 2 cases in which the system was operated and was either used or not used by the ramp drivers.

For this analysis, a method developed by Karber is used because it provides the mean, standard deviation, and variance of the mean of a set of increasing observed proportions where observed proportion is the percentage of drivers accepting a given-sized gap (8, p. 10.3; 9, pp. 201-202).

Statistical tests were made to determine whether the mean of the accepted gaps for the cases in which the green-band system was operated was significantly different from the case in which the green-band system was not operated. By use of the normal approximation relative to 2 independent data sets, one can determine whether the mean of set 1 is significantly different from the mean of set 2. The results of these tests are given in Table 16 along with critical gaps found by the Raff method. The use of the normal approximation did not permit rejection of the hypothesis that the mean gap for the system-off case is equal to the mean gap for the system-on case when drivers do not use the display. However, the normal approximation did permit rejection of the hypothesis, at the 0.10 level, that the mean gap for the system-on case when drivers use the display is equal to the mean gap for the system-off case. Thus these findings confirm the statement that the green-band system had a significant effect, at the 0.10 level, on the gap size selected by drivers.

Leading Headways After Merge

For this analysis, leading headway is defined as the headway between the ramp vehicle and the upstream highway vehicle. If drivers used moving-merge systems, the leading headway would be greater when the system was used than when no merge system was available because, with the use of the merge-control system, a leading headway allowance is applied to each highway vehicle in the freeway's right lane. As a result, the displayed green band is shorter than the actual freeway gap. The Kolmogorov-Smirnov 2-sample test was used to test the hypothesis that the distribution of leading headways is the same for the system-on and system-off cases. Based on the results given in Table 17, the evidence supports the statement that leading headways were significantly larger for that system-on case when drivers used the system than for cases when the green-band system was not used. The critical deviation would be 0.179, and the actual maximum absolute deviation between 2 distributions was 0.195. So, the distributions were significantly different at the 0.05 level.

Ratio of Relative Velocity to Highway Vehicle Velocity

Another consideration relevant to the merge process is the relative velocity between the highway and ramp vehicles involved in the merge. Drew (10, p. 201) defined a model that related time gap, T, between 2 highway vehicles upstream of the merging area to time, T′, that the ramp driver perceives as the gap length. His expression is

$$T/T' = \frac{V - V_r \cos \alpha}{V}$$

where

T/T' = ratio of actual gap to the perceived gap,
V = velocity of the upstream highway vehicle,
V_r = velocity of the ramp vehicle, and
α = angle at which the ramp and freeway converge.

This model can be used as a measure for evaluating the effect the merge-control system had on the relative speeds between merging vehicles. For the Woburn site α was 5.70 deg.

The Kolmogorov-Smirnov 2-sample test given in Table 18 failed to reject the hypothesis at the 0.05 level that the 2 distributions came from the same population. The critical deviation would be 0.179, and the actual maximum absolute deviation between 2 distributions was 0.05. So the distributions were not significantly different at the 0.05 level. Consequently, evidence suggests that at the 900 to 1,500-vph merge volume the relative behavior between the ramp and freeway vehicles was not changed when the green-band system was used at the site.

CONCLUSIONS

This report presented the results of an evaluation of freeway merge-control systems tested in Woburn, Massachusetts, in 1970. The Woburn tests were designed to determine the technical feasibility of freeway merge-control systems and whether drivers approved of the concept and used the ramp-side driver displays.

It was found that a moving-merge system was technically feasible, and the results of the analyses showed that ramp drivers approved of the concept, recognized that the systems would be used only at poorly designed ramps, and preferred the green-band system over the pacer system. It was found that drivers tended to stay within an acceptable gap more often with the green-band system than with the pacer system, and the green-band display was more consistently used by ramp drivers. Results were presented that showed that the variance of the relative velocity between the green-band edges and vehicles was significantly greater for those drivers who did not use a green band than for those drivers who used a green band. This finding also provided evidence that some drivers did use the moving green bands.

The analyses showed that the mean gap for the system-off case was significantly smaller than it was for the system-on case and that the leading headways were significantly larger when the green-band system was operated and drivers used the system than when the system was not used. Thus it was found that those ramp drivers who elected to use the green-band system and who drove beside a green band improved their positions within the freeway gap; however, they did not alter either their behavior within the acceleration lane or the behavior of the freeway traffic from what it would have been if no system had been available. That is, there was merge improvement and no traffic disruption.

These analyses are suitable for future traffic-operation evaluations and, in particular, future merge-control systems such as the green-band system being tested in Tampa, Florida.

ACKNOWLEDGMENTS

This research was part of a staff research project at Office of Research and Development, Federal Highway Administration. Appreciation is expressed to Donald E. Cleveland of the University of Michigan, who, as dissertation advisor, offered numerous suggestions and recommendations to me during the preparation of this paper. Special thanks also are due to Sidney Weiner of the Federal Highway Administration, for his suggestions of statistical analyses.

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DISCUSSION

Joseph A. Wattleworth, Department of Civil Engineering, University of Florida

Tignor has conducted a significant analysis of a freeway moving-merge system, and his results and conclusions have far-reaching effects. The nature of the study should be kept in mind when the results are considered. The 2 types of moving-merge control systems—the pacer and green-band systems—were installed at the Woburn site primarily to evaluate the hardware. The site was selected to minimize the geometric and traffic problems to allow the evaluation of the electronic operation of the systems.

The traffic-operation evaluation of the systems was a secondary aspect of the installation, and Tignor has done well in this evaluation. He compared the 2 systems and presented the following major conclusions:

1. There was no significant difference of driver opinion on the clarity of the pacer and green-band systems. About 70 percent of the drivers found the systems clear and understandable.
2. Over 70 percent of the drivers found it easy to drive beside the moving displays after they had some experience in using the systems. Experience helped the drivers understand the systems and use them properly.
3. About 70 percent of the drivers who used both systems preferred the green-band system and indicated that it was the more helpful and was easier to understand.
4. Drivers tended to stay within an acceptable gap more often with the green-band system than with the pacer system.

Thus the results of the studies that were conducted indicated that the green-band system was operationally superior to the pacer system. This is especially significant considering the fact that the cost of the green-band system is much lower than the pacer system because it requires fewer detectors on the ramp. In addition, the conceptual appeal of the open-loop, green-band system with the display representing an acceptable gap is greater to many traffic engineers than is that of the pacer system. Thus there is no need to trade off cost against effectiveness in comparing the systems. The green-band system not only is more effective but also is cheaper.

There was an apparent inconsistency in the results of the questionnaire studies that were conducted to compare the systems. A questionnaire study was conducted to determine driver evaluation of the ease of use of the 2 systems.

When the green-band system was installed, drivers who used both systems were asked to indicate which system was easier to use. The percentage of the pacer questionnaire respondents that indicated that the pacer system was easy to use was higher than the corresponding percentage of the green-band questionnaire respondents. However, in the questionnaire study conducted on the drivers who had used both systems, a greater percentage indicated that the green-band system was easier to use.

A comparison was made of the placement of ramp vehicles relative to the green with and without the display of green bands. It was found that, when no green bands were displayed, 40 percent of the ramp drivers who were in a position to possibly use the green band were positioned in such a way that they would have been beside a green band if it had been displayed. When the green bands were displayed, 67 percent of the drivers who were in a position to possibly use the green band were found to be beside a green band. Thus the green-band system can be considered to have improved the merge position and, consequently, the merge operation of 26 percent of the ramp vehicles that potentially were able to use the green band.

At first consideration, it may seem that providing a benefit to less than 26 percent of the ramp drivers is not significant. But several operational measures of effectiveness (such as delay and merge accidents) are quite sensitive to the probability of merging without a stop. Thus an increase on the order of 26 percent in merges without stopping would have a great effect not only on merge delay but also on probability of a rear-end collision in the merge area.

It was found that the average accepted gap was higher for vehicles that used the green-band display than for (a) vehicles that did not use the green-band display or (b) all vehicles when the green bands were not displayed. This would suggest that the gap portion of the program should be changed to yield lower required gaps for green-band generation. It raises a potential trade-off that must be made in evaluating the ability of the green-band system—the gap size versus the probability of merge success. By providing green bands for only relatively large gaps, the probability of a successful merge will be higher, as will the resultant safety of the merge operation, but the merge capacity will be lower. This will increase the tendency of the system to revert to a stopped mode and would increase queuing and delay on the ramp.

The results presented in the paper were based on studies conducted at a location at which merge and geometric problems were minimal. It will be interesting to compare them to the results of the evaluation of the green-band system in Tampa, Florida, where the operational and geometric problems are more severe.

In summary, the author has presented a very thorough analysis of 2 alternative approaches to a new type of freeway-ramp, moving-merge control. The results are of great practical value and provide a basis for evaluations that are being conducted in Tampa.

K. G. Courage, University of Florida

Tignor has done an excellent job of describing the evaluation of the first experiment with moving-merge control in Woburn, Massachusetts. My comments will deal primarily with a subsequent experiment with the same system that took place on the Ashley Street entrance ramp to I-75 in Tampa, Florida. The comments fall into 2 general categories: those dealing with system changes and refinements necessary to operate the green-band system in Tampa and those dealing with a preliminary evaluation of this system.

SYSTEM MODIFICATIONS

The Woburn system was developed with considerable flexibility to change operating parameters in anticipation of future deployment at other entrance ramps. It was, of course, necessary to modify detector-location parameters and various system-calibration parameters to adapt the system to the geometrics of the Tampa ramp.

Some important changes also were made to the display hardware. The green-band display itself was improved significantly through the use of a continuous row of fluorescent units as opposed to a series of discrete incandescent lamps. This change was made possible primarily because of the more favorable temperature conditions that are found in Tampa. It is not known how well fluorescent units would perform in a colder climate. Some changes in the driver information signing also were instituted in Tampa. The advanced displays that used 2 fixed-message signs with flashing signals in Woburn were consolidated into a single-lamp-matrix, changeable-message sign installed over the ramp as a gateway to the system. The sign says DRIVE BESIDE GREEN BAND whenever the system is in the moving-merge mode. In all other operational modes PREPARE TO STOP is displayed. The sign is blank when the system is inoperative. As another departure from the Woburn system, the MERGE WITH CAUTION blank-out sign in the merge area was replaced with a blank-out yield sign whose dimensions and color conform to the manual on uniform traffic devices. It also was necessary to make a number of operational software changes to adapt the system to the Ashley Street ramp. The Woburn ramp is more or less linear, but the Ashley Street ramp has a fairly sharp curve [230-ft (70.1-m) radius] on which the maximum safe speed is approximately 30 mph (48 km/h). Therefore, the propagation characteristics of the band to travel at 30 mph (48 km/h) for the first half of the ramp and accelerate to the discharge velocity of 45 mph (72 km/h) by the end of the display had to be changed. This modification also did away with the advisory speed sign indicating the constant speed at which the green band was traveling, and the elimination of the constant-speed green bands may have destroyed some of the potential benefits of merge control.

An additional change was made to the system-control logic to improve mode selection. The Woburn system was programmed to restart whenever congestion was detected in the merge area. This was found to cause problems in Tampa because of the higher level of merge-area activity. The response to merge-area congestion therefore was changed to simply mask the green bands but continue the remainder of the computational processes. Restarting is now carried out in response to an ambiguous condition arising from detector data. The conditions for changing from the moving mode to the SG mode also were altered. The Woburn system changed modes whenever the speed in the freeway right lane crossed a predetermined threshold. It was found in Tampa that because of ramp geometrics, heavy merge volumes did not cause an appreciable drop in freeway speed and that low speeds generally were observed during adverse weather only. Merge volume as measured just downstream of the entrance ramp proved to be a much more reliable parameter for this purpose. Separate volume thresholds were provided to control transition in each direction. This introduced a hysteresis effect that made the system more stable.

PRELIMINARY EVALUATION

The system has been fully operational in Tampa for approximately 2 months. Data collection and analysis are now in progress. The current status of the analysis does not permit definite conclusions to be drawn about its effectiveness. Observation, however, indicates that the system is able to generate green bands that flow into gaps in the freeway traffic and that motorists try to use the system.

On the negative side, the propagation of the band down the ramp appears to be less smooth than is desirable because of differences in speed projections obtained from the various sensors throughout the system. More refined computational algorithms would be required to improve this situation. Speeds on the ramp appear to have increased somewhat probably as a result of the green bands. However, deceleration from the end of the band display to the merge area also has increased. Approximately 20 percent of the vehicles have shown decelerations greater than 8 ft/sec^2 (2.4 m/s^2). This may suggest a lack of confidence on the part of the driver.

More definite conclusions will be based on 4 types of data to be collected and analyzed. Operational data are being collected daily from the detectors. These data will provide such information as speeds, flows, and accelerations. Limited, human-factor studies also are being carried out with test subjects in an instrumented vehicle. A public questionnaire will be distributed on the ramp to determine motorists' reactions to the system. Finally, accident reports for a before-and-after period will be analyzed to assess what, if any, improvements are attributable to the system. To date, no accidents have been recorded in which the system can be considered at fault.

Based on the limited analyses performed, I offer the following preliminary conclusions that are based largely on opinion and reflect only my views:

1. Following the green band in the moving mode of operation is not a particularly difficult task; however, some improvement in the propagation characteristics of the band (for example, elimination jerkiness) is desirable.
2. Use of the green band in the SG mode appears questionable. The distance from the stop line to the merge area is fairly short, and the acceleration characteristics of

individual drivers and vehicles vary too much to benefit substantially from an acceleration profile based on an average vehicle. The occasional absence of a green band because of the absence of a suitable gap on the freeway causes some confusion.

3. The present green-band operation is strictly open loop, that is, the propagation characteristics are not based on any information obtained from the ramp so the green bands will frequently overtake vehicles that are traveling very slowly or are stopped on the ramp. This creates a definite potential for rear-end collison on the ramp. I feel, therefore, that some feedback of detector information is required to promote safer ramp operations.

4. The complexity of the system has caused some operating and maintenance problems. System operation is extremely sensitive to malfunctioning of the input detectors, and erratic performance from any of the approximately 25 detectors can cause a complete shutdown.

Although some of these comments appear to be negative, I feel that the overall concept of the system is sound. With some mechanical improvements and sufficient driver education, the moving-merge approach to ramp control could be developed into a practical and workable traffic-control system. The question of cost effectiveness, however, is likely to limit its application to only a relatively small number of critical ramps in congested urban areas.

Herbert L. Crane, Michigan Department of State Highways and Transportation

Tignor has been comprehensive in his analysis and has done a fine job in accomplishing his stated objectives. It is understandable that, for safety, a test site with conservative geometrics was selected. I feel that the system-off data on the type of ramp for which these systems were intended would be further from the optimum that existed at the Woburn location. The reader is left with the impression that a greater contrast would exist between the system-off and system-on data at a geometrically more complex location. Even greater benefits would then be shown for that type of installation.

A questionnaire polled drivers' impressions of the need for the system (all ramps, poorly designed ramps, or not at all). Although it is impossible to determine what factors the driver considered in forming an impression, the driver was sure to notice that the quantity and the sophistication of the equipment were much greater than he or she normally encountered in similar situations. The driver also could have easily concluded that the system was very expensive. I have a strong impression that the drivers, by considering only an apparent cost rather than a consideration of cost versus benefits, would be inclined to be negative in their answers.

I wonder whether the level of difficulty in driving beside the display refers to the hardware or to the strategy because both of these parameters were changed at the same time. This may imply the need for a third candidate system, such as one with green-band hardware and some of the pacer system's updating logic.

The use of questionnaires for base data dictates that the driver respond to the questions at some time after his or her performance in the system. The longer the wait before the driver fills out the questionnaire, the more prone he or she is to have lapses of memory or mistaken impressions. It would be interesting to measure the driver's reactions to the systems by visual evidence of compliance. I recognize, however, that to supplement Tignor's work with such a study would be costly, time consuming, and difficult to analyze.

The provision for a leading headway allowance, resulting in a shorter green band, is obviously necessary for safety. It is possible that this provision might have introduced the driver onto the freeway at a headway other than that which he or she usually considered comfortable. This would suggest that some drivers may have responded to the questionnaire in a negative way even though they benefited by the system.

The indication that relative behavior between the ramp and freeway traffic in the merge area was not changed by the green-band system suggests that the conservative site was an optimal design for the traffic conditions encountered. I would expect stronger differences between system-off and system-on statuses to occur on more critical ramps.

Tignor has stated that merge control is intended to be used at substandard ramps where drivers experience difficulty in merging and where reconstruction of the merge area is infeasible. He has addressed himself to the problem adequately for the intended scope of his work. I feel that his statement deserves support and emphasis because some of the applications are less apparent than others. The most apparent application is its use on ramps with critical sight restrictions, short merge lanes, and other similar features. Less apparent are those in which the aforementioned features are adequate but contain other geometric features that make the ramp drivers' evaluation of freeway gaps difficult to evaluate. The best example of this would be a circular ramp of minimum radius. In this case the driver must remain intent on the task of tracking around the curve and, at the same time, try to find and evaluate a gap in traffic on a roadway to which the angle of approach is constantly changing. All the while, the driver must keep his or her vision fixed on the ramp, which is curving to the right, and the gap on the freeway, which has a motion toward the left periphery of his or her vision because of the rotational component of his or her own motion. The introduction of a moving-merge guide display close at hand tends to bring the visual references into a more narrow and constant field of vision to which the driver can more readily relate.

AUTHOR'S CLOSURE

I would like to thank Wattleworth, Courage, and Crane for their reviews of the moving-merge system tested in Woburn, Massachusetts. The points they made will be very helpful in providing further improvements in the moving-merge concept. It was particularly interesting to learn from Courage's remarks that the preliminary results from the Tampa questionnaire were similar to the results obtained in the Woburn tests. Several specific points were raised by the reviewers that require additional discussion.

Wattleworth stated the percentage of respondents to the pacer questionnaire (the first system tested indicating that the pacer system was easy to use was higher than the corresponding percentage for the green-band system. These results were taken from the question concerning the degree of difficulty in using the moving-display lights. For 2 reasons the individual system questionnaire results should not be jointly compared. First, not all drivers used both systems, and second, the basis of how individual drivers determined level of difficulty was not uniform for each system. For example, a driver may have answered the question for the pacer system while subjectively comparing it to no system. For the green-band questionnaire, a driver could have subjectively compared the green-band system to both the pacer system and no system. The last question of the green-band questionnaire was included to permit a system-to-system comparison. This question is believed to provide the most accurate information on ease of use because only those drivers who used both systems were considered.

Courage stated that the propagation of the band is sometimes interrupted or disturbed because of differences in speed projections obtained from the various sensors. He suggests that a refined green-band algorithm is needed to stabilize the propagation of green bands along the driver display. This suggestion appears to have considerable merit, and it should be considered for future system installations.

Courage also stated that the preliminary results indicated that the ramp speeds have increased but that there also had been some increase in deceleration from the end of the display to the merge area. He further stated that 20 percent of the drivers might have been electing to slow down or not merge when they had a green band. It will be interesting to see after several months of operation what effect additional driver use and system operation will have on this preliminary finding.

The SG mode was designed to permit drivers to relate to the location of the freeway gap and thereby more readily merge into it. Courage's comments suggest that the acceleration profile being used in Tampa requires drivers to accelerate either faster than they desire or faster than their vehicle will permit. A slower acceleration profile may be necessary. If a suitable acceleration profile cannot be determined that a reasonable number of vehicles can use, it may be best, as Courage suggested, not to use the SG mode. However, it is my view that the SG mode can be very helpful and should be maintained as a driver aid.

The green-band operation uses an open-loop control concept. Courage expressed some concern about green bands overtaking slowly moving ramp vehicles and suggested that some feedback mechanism be included. At present system feedback and overriding provisions are included in the green-band software. For example, whenever vehicles are stopped within the acceleration lane for longer than 5 sec, the display is blanked out until the acceleration lane is clear. This safety override appears sound when one considers that drivers do not lock into moving green bands but monitor other ramp vehicles.

One of the provisions included in the Tampa green-band evaluation plan provides for a cost-effectiveness analysis. This analysis will identify those applications in which the use of the green-band system will be the economically preferred plan. Experience in Tampa indicated that an operating moving-merge system may cost between $125,000 and $150,000 with an annual maintenance and operation cost of $5,000 to $10,000.