EVALUATION OF THE EFFECTIVENESS OF RAMP METERING OPERATIONS

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ABSTRACT

Ramp metering violations were reduced from 40% to 10% when an explanatory sign reading "ON GREEN ONE CAR ONLY" was installed on two entrance ramps of the John C. Lodge Freeway in Detroit. At one ramp, the amber aspect was removed from the signal and the termination of the green signal was controlled by a detector just downstream of the signal. A new metering strategy based on keeping vehicular storage, estimated from the calculated total travel and the average speed between detector stations, in each subsystem within allowable limits was developed. The revised strategy produced a reduction in ramp queue delays but not in the estimated total travel on the freeway. The use of a temporary constant green indication at a severely congested metered ramp allowed excessively long queues to be discharged and normal metering used during much of the peak period. A pilot study of the effect of wet pavement on freeway operations showed no significant changes in capacity or free speed. A comparison of accident experience on the entrance ramps before and after the installation of ramp metering indicated no significant change in the accident rate although the number

of accidents increased after installation of ramp metering. There was also no significant decrease in the incidence of on-freeway accidents that might be attributable to the beneficial operational effects of freeway surveillance and control.

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DISCLAIMER

The opinions and conclusions expressed or implied in this report are those of the research agency. They are not necessarily those of the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, or of the individual states participating in the National Cooperative Highway Research Program.

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SUMMARY OF FINDINGS

Several traffic control changes were made on the eight metered John C. Lodge Freeway ramps to reduce the number of violations taking place. Before additional control devices were installed or modifications made to existing control devices, violation rates of up to 40% were prevalent. These violations consisted primarily of drivers passing through on the amber phase behind the lead vehicle. The metering installations consisted of a three-aspect signal head midway down the ramp and a sign warning motorists of the presence of metering at the head of the ramp. Significant reductions in the violation rate were obtained when an explanatory sign reading "ON GREEN ONE CAR ONLY" was installed at two ramps. One vehicle in ten, however, still violated the signal in the above manner.

At one ramp the amber aspect was removed from the signal head and one of the existing loop detectors was used to record the passage of a vehicle and change the green signal to red. Pavement markings were added to encourage drivers to center their vehicles over the presence detectors at the metering installation. Although these additional modifications should have further improved the ramp metering scheme, the study revealed that there was no additional reduction of the violation rate.

The presence of the warning sign, "RAMP METERED WHEN FLASHING," at the head of the ramp had no effect in reducing violations. It is recommended, however, that the sign be retained for reasons of safety and good traffic engineering practice.

A new ramp metering strategy based on keeping subsystem storage, estimated from the calculated total travel and the average speed between detector stations, within allowable limits was developed. The new strategy was found to reduce ramp queue delay by 30 vehicle hours per day and ramp congestion occupied a smaller portion of the peak period. No significant change was found in total freeway travel or total travel time.

Ramp congestion problems at the Davison Expressway to northbound Lodge Freeway entrance ramp were overcome by employing a constant green indication at the signal to clear congestion when the queue intruded on the traveled way on Davison. Suspending the metering even temporarily was undesirable for the control of freeway operations, but this modification did reduce the severity of the problem and allowed regular metering operations to resume.

A limited study of environmental factors showed no significant effect of rain on freeway capacity or free speed.

All of the accidents occurring on the entrance ramps were of the rear-end type. The installation of ramp metering control did not generate a significant change in the number of accidents on the entrance ramps although there were more accidents after ramp metering was installed. A study of on-freeway accidents, both before and after the implementation of surveillance operations, found no significant decrease in the accident rate.

PART ONE

CHAPTER ONE

INTRODUCTION

In 1967 the Texas Transportation Institute (TTI) installed a ramp traffic sensing and control system to meter the operation of eight entrance ramps to the northbound John C. Lodge Freeway in Detroit as shown in Figure 1 (34)*. Ramp metering is the functional basis of a digital computer freeway corridor surveillance and control system. By limiting the rate at which vehicles enter the freeway, the ramp metering controls the freeway level of service.

One goal of ramp metering is to keep freeway demand within acceptable levels as determined by the desired level of service on the freeway. For drivers already on the freeway there should be tangible benefits in terms of less congestion during the peak period and more orderly merging movements at the entrance ramps as a consequence of metering. Researchers in Detroit, Chicago and elsewhere have noted statistically significant decreases in the duration of peak period congestion (9, 17, 27). A benefit resulting from less congestion and fewer merging conflicts could well be a reduced

*Numbers refer to references at end of Part One of this report.

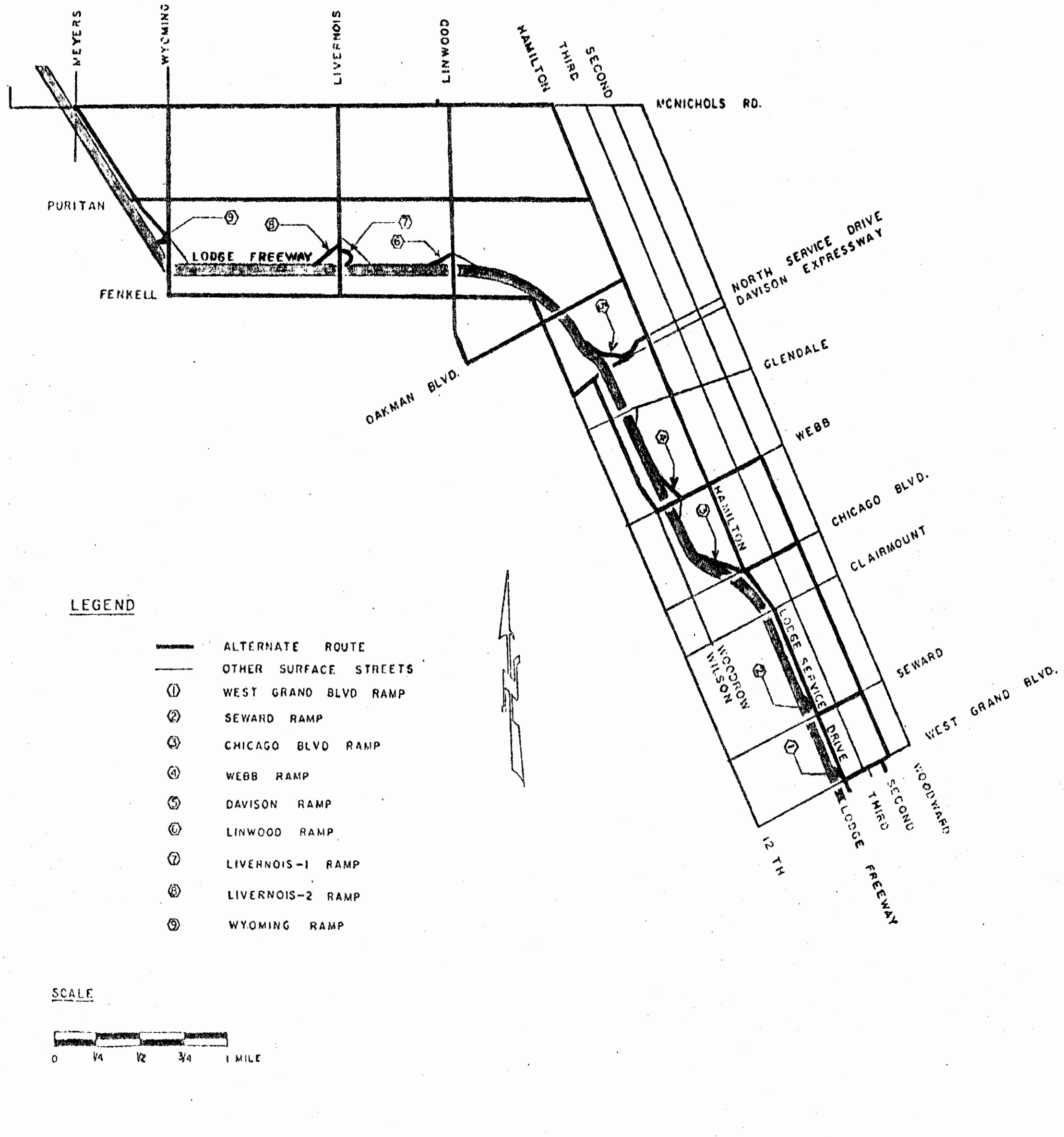

FIGURE 1

MAP OF LODGE FREEWAY CORRIDOR
SHOWING METERED RAMPS

accident rate on the freeway. The reduction of merging conflicts benefits the ramp user as well. A study of rear-end collisions on an entrance ramp in Atlanta where the acceleration lane was of insufficient length showed that ramp metering brought about a 90% reduction in these collisions (32). The metering virtually eliminated conflicts resulting from vehicles stopping at the foot of the ramp prior to merging. Ramp metering installations thus can compensate for substandard geometric features and perhaps reduce accidents on the entrance ramps. Of more concern on the Lodge Freeway was the possibility that these installations would increase accidents. The very presence of ramp metering is contradictory to the function of entrance ramps. Having vehicles stop on the ramp at least increases the possibilities of rear-end collisions.

The benefits accruing to on-freeway users are at the expense of the ramp user whose travel time is almost inevitably increased as a result of ramp delay unless improved freeway operations allow him to compensate for the time loss with a quicker freeway trip. One consequence of increased ramp delay is the diversion of shorter trips to surface street alternate routes in the corridor (Figure 1). The corridor operations are improved because these drivers experience little additional delay in their short trips while their removal from the freeway lessens demand and reduces the number of merging conflicts at entrance and exit ramps. For the remaining drivers who will experience delay, compensation at least can take the form of providing an attractive alternate route to their destination. This was the central objective of the 1969 research program in the Lodge Freeway Corridor.

The research efforts into the operation of alternate routes are presented in other reports (28, 29). This report contains several investigations of the effectiveness of the ramp metering operation itself. The investigations were necessarily diverse because of the variety of effects generated by ramp metering. The studies were as follows.

Certain hardware modifications were made at the metering installations to present a more effective display to the ramp user. The objective of this effort, presented in Chapter Two, was the reduction in ramp metering violations where more than one vehicle passed through on the green phase. The Texas Transportation Institute (TTI) had not been taking these violations into consideration in their control strategy although their Final Report noted violations "as high as 40% on some ramps" (9). Whether taken into consideration or not, a control problem existed especially when the freeway was operating near capacity and minimum metering rates were necessary. Continued disobedience would only have fostered a lack of respect for ramp metering installations. It was also a moot question as to whether disobedience was truly present. Most of the entrance ramps allowed one vehicle through at a time primarily on the strength of a fixed and very short green time. Total green and amber time amounted to three seconds. Considering a possible driver response time of a second, combined with the downgrade at all the ramps, a driver following the lead vehicle could well be in motion before the red indication.

Another major effort in 1969 was the investigation of the control logic for ramp metering. The TTI control strategy was evaluated and an alternative method for control based on estimating the number of vehicles within a freeway subsystem was developed and tested. A subsystem was defined as a length of freeway bordered by on-freeway detector stations and containing one entrance ramp. It was anticipated that the new strategy would overcome several problems in the TTI strategy and render the surveillance system more responsive to accidents and other capacity-reducing incidents on the freeway. A full description of this portion of the research is presented in Chapter Three. Potential benefits in terms of reduced total travel on the freeway and reduced ramp queue delays were investigated.

Ramp metering created a serious congestion problem at the Davison entrance ramp. Ramp queues occasionally intruded on the shoulder lane of the Davison Expressway to create a hazardous situation. Modifications in the ramp metering strategy at Davison to alleviate this situation are presented in Chapter Three. Also included in Chapter Three is a pilot study of environmental effects on freeway operations. The behavior of traffic in inclement weather was studied in order to determine if the ramp metering control strategy should take environmental factors into account.

Two other studies concerned with the effects of ramp metering on the accident rate, both on the freeway and at the ramps, are presented in Chapter Four. As indicated above, a possible benefit of ramp metering would be a reduction in the on-freeway accident rate as a result of smoother traffic operations. Similarly, an analysis of accidents on the entrance ramps was done to determine if the presence of ramp metering adversely affected the accident rate as a result of having vehicles stopped on the ramps.

CHAPTER TWO

MODIFICATIONS AT RAMP METERING INSTALLATIONS

RAMP METERING INSTALLATION REDESIGN

The original ramp metering installations, installed in 1967 by TTI, consisted of a standard traffic signal head mounted midway along the ramp, an explanatory sign mounted below the signal, a painted white stop bar on the pavement adjacent to the signal, a warning sign with amber flasher at the head of the ramp alerting motorists to the presence and operational status of the metering, and induction loop presence detectors (34).

The signal head, installed at a low level and adjacent to the left side of the ramp, consisted of standard red, amber, and green aspects. The explanatory sign below the signal was white with black lettering and read "Stop Here On Signal." The sign also bore an arrow indicating the location of the white stop bar. In the early phases of ramp metering research, it was found that the "Stop Here For Signal" sign was a source of confusion for some motorists, and the signs were later modified to read "Stop Here For Red."

The yellow warning sign was diamond-shaped in conformance with standard traffic engineering practice. A flashing amber signal was installed above the sign to better call attention to the sign message -- "RAMP METERED WHEN FLASHING."

Vehicle presence near the signal was detected initially by a six-by-six foot loop detector located immediately upstream of the ramp signal. These detectors were assigned two functions by TTI, vehicle counts and ramp metering. It was recognized at the time that this arrangement was undesirable from an operational standpoint -- some vehicles were stopping before reaching these loops and were thus not being detected.

At six of the ramps the metering strategy allowed one vehicle at a time to pass through the signal up to a maximum of twelve vehicles per minute. Each entering driver was always presented with a red indication at the signal. If no vehicles approached it, the signal would remain in the static red state. Thus, every driver was required to stop at the ramp signal, and drivers were to proceed through one vehicle at a time. This was done by making the green period so short, 1.5 seconds followed by 1.5 seconds of amber, that only one vehicle could legally pass through. The day after ramp metering began, a local newsman wrote "The West Chicago ramp signal turned green only for a flash, and drivers needed a drag-racing start to make it past the signal legally."[1] The 1.5 second green phase, however, did generally prove to be adequate for one vehicle to pass through.

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[1] Detroit News, July 7, 1967, Jon Lowell.

In the absence of any other explanatory devices, it was expected that the driver would treat the ramp metering signal as he would any other traffic signal. The logic behind the single service ramps was never thoroughly presented to the public. The informational leaflet passed out to ramp users the first day of ramp metering informed the motorist that "you are legally required to stop for this light just as you are for any similar traffic signal on any street" (34). Considering the experimental nature of these installations this statement may not have been entirely true, but the success of the system depended on motorists respecting the signal.

In the publicity surrounding these first installations, little emphasis was placed on the one-vehicle-at-a-time strategy so essential to the metering (34). The emphasis instead was on slowing down the rate of ramp entries and diverting some potential freeway users to other routes because of increased ramp delay. In fact, the informational leaflet handed ramp users never clearly stated that only one vehicle should pass on green. The leaflet read:

> "When the light turns green, the first car should proceed and should be able to merge with traffic on the freeway. ... Normally the green will be on only long enough for one car to get

> through,... ...you are urged to keep alert and be prepared to stop when the light turns yellow, as you are at any surface traffic signal."

Violations perhaps would have been reduced had motorists been presented with a more adequate explanation.

The 1969 TTI Final Report noted a violation rate at the metering signals "as high as 40% on some ramps." Most of these violations consisted of two consecutive vehicles passing through on the green cycle when time was allotted for only one vehicle (9). Since the green cycle for single service ramps consisted of 1.5 seconds of green followed by 1.5 seconds of amber, it was evident that violators were "running the yellow light." They were, indeed, treating the metering signal as they would a traffic signal to the detriment of control operations. Any apparent disrespect for any of the metering devices was of concern.

It was evident that there was a surveillance control problem as well. The magnitude of the violation rate was such that when the minimum metering rate of three vehicles per minute was imposed, the actual entry rate exceeded four vehicles per minute. It was often desirable to allow even fewer vehicles onto the freeway in a given minute as a result of downstream congestion. Violations compounded the surveillance problem in these cases, since a desired entry rate of two, one, or no vehicles would still result in an actual four vehicles entering the freeway. There was no way to take violations into consideration by discounting the computed metering rate as there would be for higher rates. The project was constrained to a maximum cycle time of 20 seconds, both for political reasons and the assumption that ramp users would not tolerate longer delays.

As a result of these problems, changes in the ramp metering installations were made in 1969 in an attempt to reduce the violation rate. Most changes were made only at the Seward ramp, the location of the highest violation rate (Figure 2). The three-aspect signal was replaced with a two-aspect signal, the signal was moved up the ramp 16 feet to a location between the two existing in-pavement loop detectors, a new sign was placed near the signal and channelization markings were added.

Additional loop detectors had been installed previously by Texas Transportation Institute in 1969 on all the entrance ramps to lessen the possibility of vehicles not being detected when stopped at the signal. The new detectors, measuring twelve feet by six feet, were located six feet upstream of the original detectors.

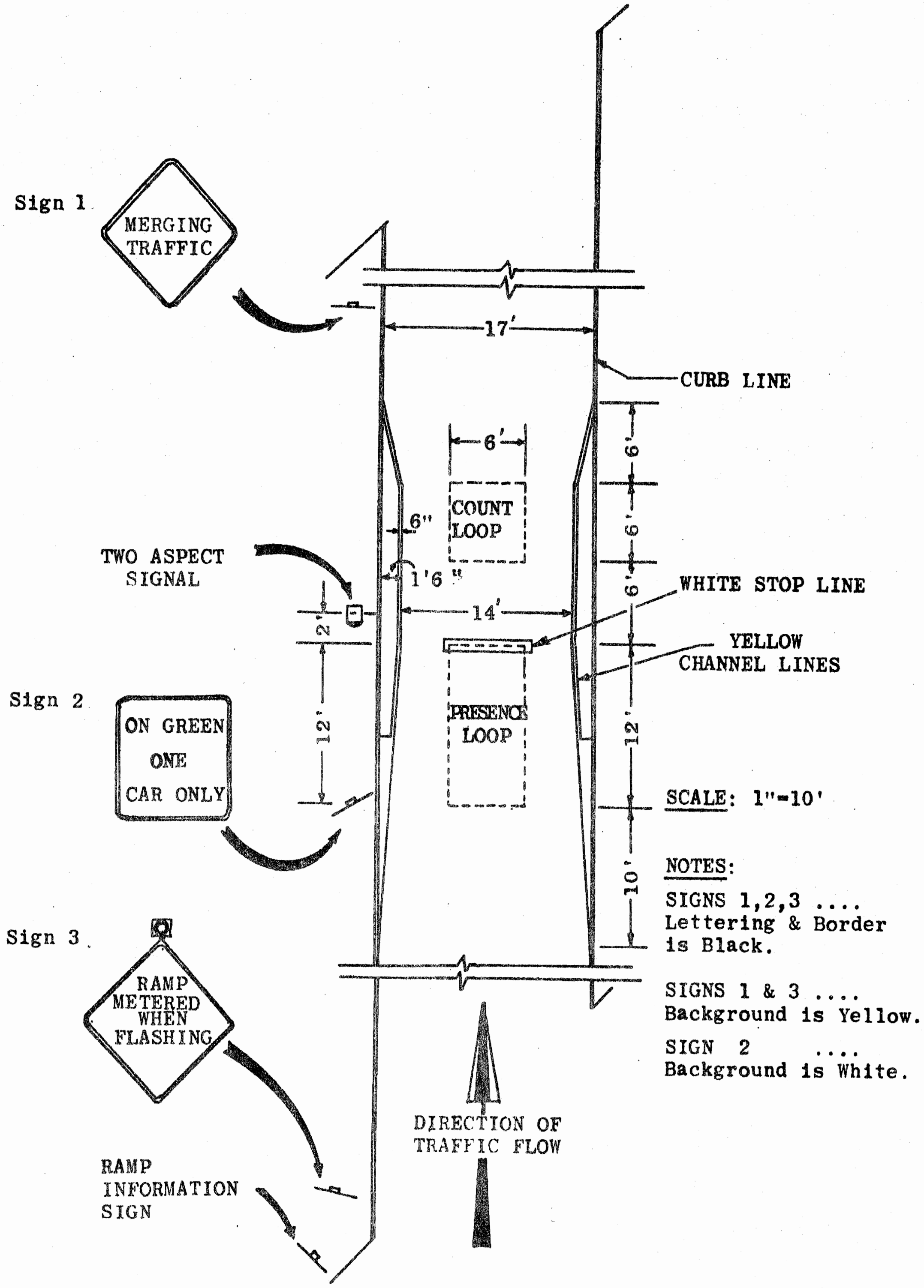


FIGURE 2

SEWARD RAMP METERING DEVICES

The removal of the amber aspect was intended to make it more difficult for a second entering driver to avoid violating the red aspect. It was felt that violations did not necessarily imply disrespect for the signal. "Running the yellow light" is a common practice at signalized intersections that is perhaps transferred to ramp signals. Considering the incomplete explanation of single service ramp metering by TTI and the fact that two ramps, West Grand Boulevard and Davison, did allow multiple entries on green, it was considered desirable to inform drivers explicitly of their required response at the signal. Hence, to reinforce the removal of the amber aspect at Seward, a regulatory "ON GREEN ONE CAR ONLY" sign was designed to replace the existing sign at the metering signal (Figure 3). This sign was also placed at the Chicago ramp.

With the smaller loop detector downstream from the metering signal, it was then utilized as a confirmation detector of the passage of a vehicle. When a vehicle crossed it, the green indication immediately changed to red. This arrangement provided just enough green time for one vehicle to pass the signal and yet gave additional flexibility to allow for the occasional slow responding driver.

SPECIFICATIONS

1. "On," "Green," "Car" and "Only" to be 4" Series D
2. "One" to be 6" series E
3. Lettering and Border to be Black
4. Background to be Reflectorized White

FIGURE 3

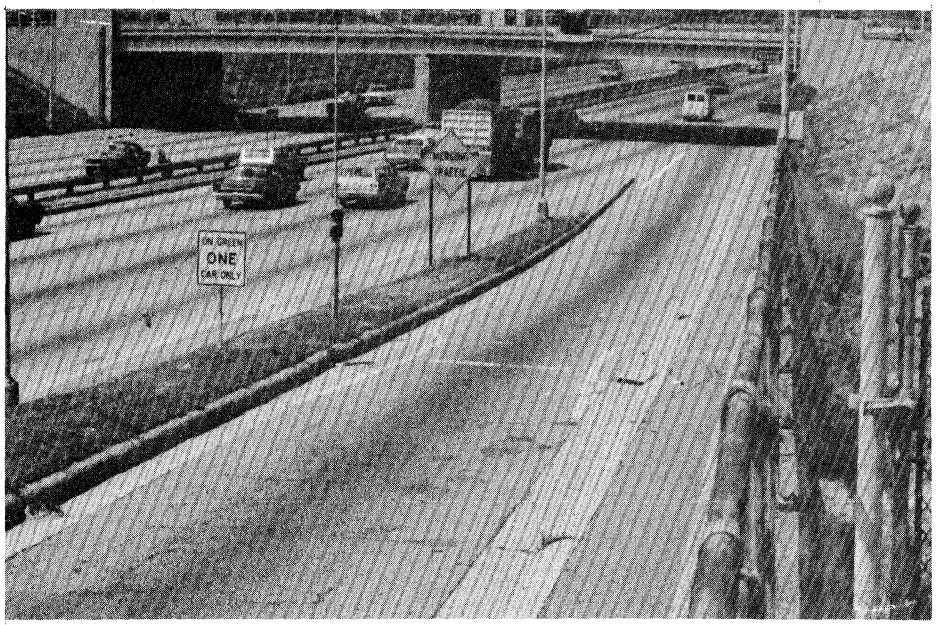
"ON GREEN ONE CAR ONLY" SIGN

The modifications at Seward diagrammed in Figure 2 are illustrated in the upper part of Figure 4. The signal head was moved to a point two feet downstream of the upstream loop detector, which continued to function as a presence detector. The stop bar was placed at the downstream end of this loop detector. The design layout was such that the next vehicle waiting at the signal could not reach the stop line without encountering a red signal. The yellow channelization markings were included to encourage drivers to center their vehicles over the presence confirmation detectors. The "RAMP METERED WHEN FLASHING" sign with its flasher was later removed at the Chicago ramp.

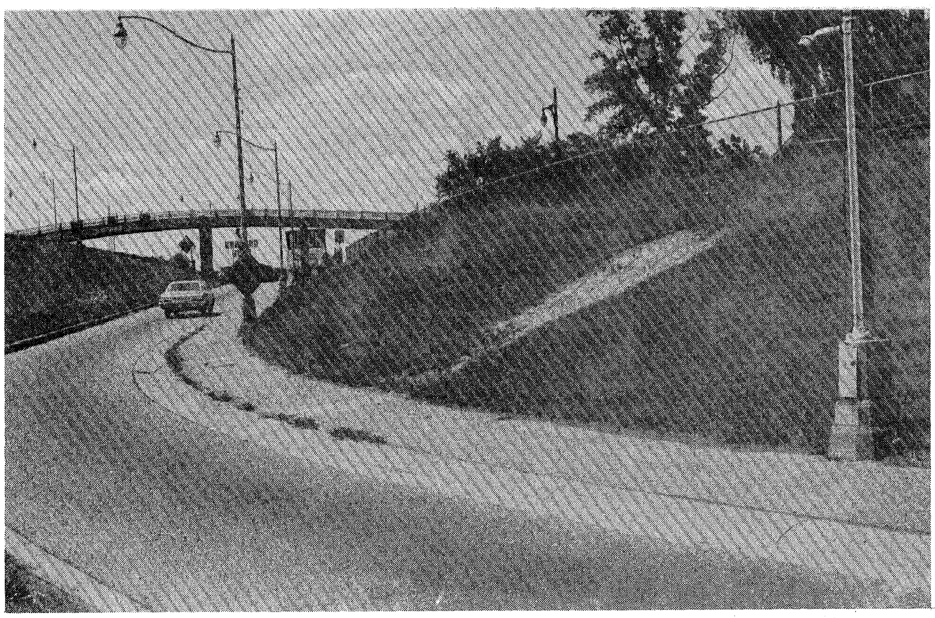
RESEARCH APPROACH

"Before" and "after" studies of the violation rate for the above set of modifications were made at the Seward ramp. Violation data were obtained from computer records by comparing the number of green indications with the number of vehicles recorded entering the freeway. Excess vehicles were violations. These data were confirmed by visual inspection of traffic operations at Seward after the modifications were made by means of the television surveillance monitors.

In order to isolate the effects of the "ON GREEN ONE CAR ONLY" sign, the sign was installed at the Chicago ramp



TRAFFIC CONTROL DEVICES AT SEWARD RAMP



DAVISON-LODGE BULK-SERVICE RAMP METERING INSTALLATIONS

FIGURE 4

RAMP METERING INSTALLATIONS

without any of the other modifications being done. A similar violation study was then done at Chicago and the results compared with the Seward ramp. Also at the Chicago ramp the impact of the removal of the "RAMP METERED WHEN FLASHING" sign on the violation rate was studied. This latter study took place several months after the study of the explanatory metering sign.

EFFECTIVENESS OF THE "ON GREEN ONE CAR ONLY" SIGN

In July, 1969, the "ON GREEN ONE CAR ONLY" sign was installed at the Chicago ramp in order to determine the effect it would have on the violation rate. The unit of comparison chosen was the number of violations per five-minute interval. This information was compiled automatically by the computer which compared the number of green indications per five-minute interval with the actual number of vehicles that went through during the interval. It was assumed that the interval was long enough for successive observations of violations to be independent. Should violations be randomly occurring events, it was expected that the number of violations per interval would vary directly with the volumes per interval. At low volumes, however, the opportunity for violation would be less owing to the preponderance of one vehicle ramp queues. At very high demand levels traffic pressure in terms of long queues and waiting times might induce additional violations. These effects were investigated by means of direct television observation of metering operations at the Chicago ramp. Also, a plot of five-minute volumes versus violations for one day disclosed an approximately linear relationship with no evidence of bias.

Before the installation of the sign, the average number of violations per five-minute interval was 3.36 for a sample of 287 intervals. After the sign installation, the violation rate was reduced 81% to 0.48 violations per interval for 710 intervals. Application of the "t" test showed that this large reduction of the violation rate was statistically significant at the 0.01 level.

Additional violation studies were conducted by observation of traffic operations at the Chicago ramp by television surveillance personnel. A "before" study was conducted from 3:45 p.m. to 5:15 p.m. on July 14, 1969. During this period, there were 291 opportunities for violation: An opportunity consisted of at least two vehicles waiting at the signal. There were 81 violations observed, a violation rate of 28%. Of these 81 violations 22 were by drivers who had witnessed a prior violation by a vehicle ahead of them. During one interval there were six such consecutive violations involving a total of 12 vehicles. This is a statistically significant indication that seeing a violation encourages other drivers to do likewise. In addition, five vehicles ignored the red light when no other vehicles were present and entered the freeway without stopping.

A similar "after" study was conducted from 4:00 p.m. to 5:15 p.m. on August 1, after the installation of the "ON GREEN ONE CAR ONLY" sign July 28. Out of 200 opportunities for violation, 20 were committed, a violation rate of 10%. A binomial difference test was significant at the 0.01 level, providing a strong indication that the sign improved signal obedience.

Of the 20 violations, only two were by drivers who had witnessed a previous violation, a result indicating the success of the sign in reducing the interactive disobedience observed in the "before" study.

EFFECTIVENESS OF THE FULL SET OF RAMP METERING MODIFICATIONS

The effect of the four modifications (addition of explanatory sign, removal of amber aspect, use of confirmation loop detector to terminate green phase, and pavement channelization markings) made to the ramp metering system at Seward was studied. This ramp was the most troublesome ramp in the system in terms of violations. The observed violation rate here was 46%, higher than that at any other ramp. The violation rate was determined by dividing the total number of violations for three peak periods by the total volume during these same periods.

Six peak periods, three "before" and three "after," were randomly selected for analysis. Before the modifications were made, the average number of violations per five-minute interval was 14.11 for 144 intervals. After the installations, the violation rate was 2.54 for 143 five-minute intervals, a decrease of 82% in the violation rate. Again, application of the "t" test showed that this decrease was statistically significant at the 0.01 level. The violation rate, based on volume, had decreased from 46% to 11%.

A visual study of operations at the ramp after the above modifications were made was conducted between 3:45 and 5:20 p.m. on July 15. Of the 348 opportunities for violation, only 37 occurred for a rate of 10.6%. Of these violations, seven were committed by drivers witnessing earlier violations.

Despite the somewhat heavier traffic volumes and consequently longer delays for drivers at Seward than at Chicago, there is no apparent difference between the violation rates at these two ramps. A chi-square test performed on the "after" data for the two ramp locations confirmed this belief.

Long queues were observed during the peak period at Seward. Occasionally, very long waiting periods between signal changes were noted, including one of 50 seconds (despite a maximum of 20 seconds set in the computer controller). These very long waits did not generate violations by the lead vehicle nor the following vehicles. Between 4:30 and 5:20 p.m. the ramp queue contained six vehicles or more at all times, but violations were still infrequent and occurred only randomly. Only once did two vehicles abreast pass through the ramp signal, indicating the general effectiveness of the pavement markings.

Based on these observations at the Seward and Chicago ramps, it appears that one vehicle in ten will violate the ramp signal when the opportunity presents itself. Outright violations of the red indication are infrequent and are not considered a significant problem.

The modifications made at Seward were all considered desirable. The pavement markings appeared to be effective in preventing vehicles from moving two abreast past the signal. The removal of the amber aspect, redundant for single service metering schemes, and the use of a flexible green time both certainly made it more difficult for violators to avoid passing on the red indication. However, the experience at Seward and Chicago indicated that the key modification was the "ON GREEN ONE CAR ONLY" sign. It is possible that for the first time drivers were informed in explicit terms of the expected response to the ramp metering control signal.

EFFECTIVENESS OF THE "RAMP METERED WHEN FLASHING" SIGN

The destruction of the "RAMP METERED WHEN FLASHING" sign in an accident at the Chicago ramp in mid-October, 1969, provided an opportunity to measure what effect, if any, this warning sign had on the violation rate. It was believed that the presence of the ramp condition information signs may have eliminated the need for this warning sign, particularly at West Grand Boulevard and Seward where the new signs were adjacent to the warning sign (28).

The study extended over the evening peak period from 2:30 to 6:30 p.m. for a number of days before and after the removal of the sign. A study of 710 five-minute intervals with the sign still in place revealed a rate of 0.476 violations per interval. There was an average of 0.478 violations per interval for 1967 peak intervals when the sign was no longer present. Assuming average traffic volumes per interval to be the same before and after the removal of the sign, there was no important (or statistically significant) change in the violation rate as a result of this change in the advance display device.

In a sense, this result was to be expected since the extremely effective "ON GREEN ONE CAR ONLY" sign was present for both the before and after studies. An increase in violations would have meant that drivers were disobeying this sign as well as the metering signal. Since violations did not increase, it is concluded that the sign is not operationally necessary for the majority of drivers.

The "RAMP METERED WHEN FLASHING" signs were originally installed by TTI for reasons of good traffic engineering practice as ramp metering was a new concept (34). Having to stop on an acceleration ramp is inimical to the ramp's purpose and it is reasonable to provide a warning sign to alert the driver to such an unexpected condition ahead. The primary purpose of the sign is safety -- the prevention of rear-end collisions by approaching vehicles with other vehicles stopped on the ramp -- rather than the prevention of violations. The effectiveness of the sign in that regard might be inferred from the accident experience presented in Chapter Four. Ramp metering had existed for over two years at the time of this study, but it was concluded that the sign still served a useful and needed function for drivers unfamiliar with ramp metering. Those drivers that used the ramp every day may have been so accustomed to the situation that they never missed the warning sign during the study.

CHAPTER THREE

MODIFICATIONS IN RAMP METERING CONTROL STRATEGY

The basic control strategy for ramp metering was to keep sufficient vehicles off the freeway to maintain a level of service which would allow traffic to move at speeds of at least 45 miles per hour. To achieve this, the Texas Transportation Institute (TTI) used a "demand-capacity" mode of operation in which the flow measured upstream of the ramp, representing the traffic demand, was compared with the predetermined downstream capacity (34). The metering rate was determined from the difference between capacity and demand. The freeway was divided into "subsystems," each containing one entrance ramp and bordered by detector stations. Each detector station had overhead sonic detectors for every lane of traffic to provide the volume and occupancy inputs necessary for this metering control strategy. The network of detector stations was incomplete when The University of Michigan commenced its research in 1969. Ten overhead sonic detectors were installed in 1969 on the Oakman, Dexter, and Greenlawn overpasses to improve the ramp metering capability in the northern half of the freeway corridor.

The presence of ramp metering had increased congestion problems caused by ramp queue lengths. TTI had used a higher capacity metering strategy at the two busiest entrance ramps (West Grand Boulevard and Davison), but this still resulted in unsatisfactory operations at these ramps. The Department of Streets and Traffic was particularly concerned with the effects of the metering on safety and operations at these locations.[1] A special study to determine the feasibility of relaxing ramp metering at the Davison Expressway to Lodge Freeway ramp at times of intolerable ramp congestion is presented in this chapter.

Other than the modifications in strategy necessary at Davison, the central objective of the 1969 investigations of the metering control strategy was to improve ramp operations while maintaining an acceptable level of service on the freeway. The feasibility of taking into consideration both dry and wet pavement conditions in the control strategy is also presented in this chapter. Parallel studies to improve ramp operations through use of ramp condition information and variable message signs are presented in other reports (28,

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[1]Malo, Alger F., Private Communication.

29). The function of these signs was to divert sufficient ramp traffic to reduce ramp congestion.

RAMP METERING STRATEGY REVISION

The Texas Transportation Institute has developed two basic approaches to ramp metering strategy. TTI employed the demand-capacity approach mentioned above on the Lodge Freeway. In another freeway surveillance project TTI developed a gap acceptance strategy (4). Information on the time headways between vehicles in the shoulder lane of the freeway was used to determine the existence of acceptable gaps for ramp vehicles. The release of the ramp vehicles was then timed to promote a more efficient merge into the traffic stream. After study, it was decided not to allot any project resources to compare these approaches but to attempt to overcome the difficulties associated with operations of the demand-capacity mode of operation.

The literature on system-controlled ramp metering (metering based partly on operations in other subsystems) was reviewed. (See the most significant publications in the list of references following Chapter 6.) There was no apparent reason to make major changes in the present approach since it was not likely that any alternative in which upstream metering was based on downstream congestion would bring significant improvements. The TTI strategy contained some provision for system operation in that excessive demand in a subsystem resulted in metering adjustments in the subsystem immediately upstream to reduce the demand. It was expected that operation of the freeway corridor to divert potential freeway users, particularly those with short trips, to alternate surface routes would provide genuine system operation with the maximization of vehicle miles of travel on the freeway.

Two alternative demand-capacity strategies had been tested by TTI in Detroit (9). The first strategy, "real-time" control, counted input and output volumes as they were received by the computer rather than using one-minute totals. The technique was found to be too sensitive to changes in demand, however, and did not give satisfactory performance. The alternative strategy actually used by TTI was "pseudo real-time" control where fixed metering rates were updated every minute rather than every second.

To guarantee lower metering rates during congested periods, pseudo real-time control reduced the maximum metering rates whenever freeway speeds dropped below two-thirds of the predetermined free-flow speed. The basic traffic parameter for this strategy was the available capacity in the n^{th} subsystem, A_n, the use of which is illustrated in Figure 5. A_n was assigned a positive value if the occupancy at the detector station immediately downstream of the ramp was less than the occupancy for maximum flow. Otherwise, a negative value was assigned. For an isolated subsystem containing one entrance ramp, a negative A_n would indicate that freeway capacity was exceeded at the entrance ramp, and minimum metering rates established by policy considerations would be used. If not, the metering rate was set equal to the available capacity using the following quadratic relationship:

$$A_n = \begin{cases} C[1 - 2(\theta/\theta_c) + (\theta/\theta_c)^2], & \theta \leq \theta_c \\ -C[1 - 2(\theta/\theta_c) + (\theta/\theta_c)^2], & \theta \geq \theta_c \end{cases}$$

where C is the freeway capacity in the n^{th} subsystem

θ is the occupancy in the previous minute

θ_c is the occupancy for maximum flow

Then the metering rate is:

$\theta \leq 2/3\ \theta_c$	The maximum rate
$2/3\ \theta_c \leq \theta \leq \theta_c$	A_n, if A_n is not less than the minimum rate nor more than the maximum rate. Otherwise, use the minimum or maximum rate.
$\theta > \theta_c$	The minimum rate.

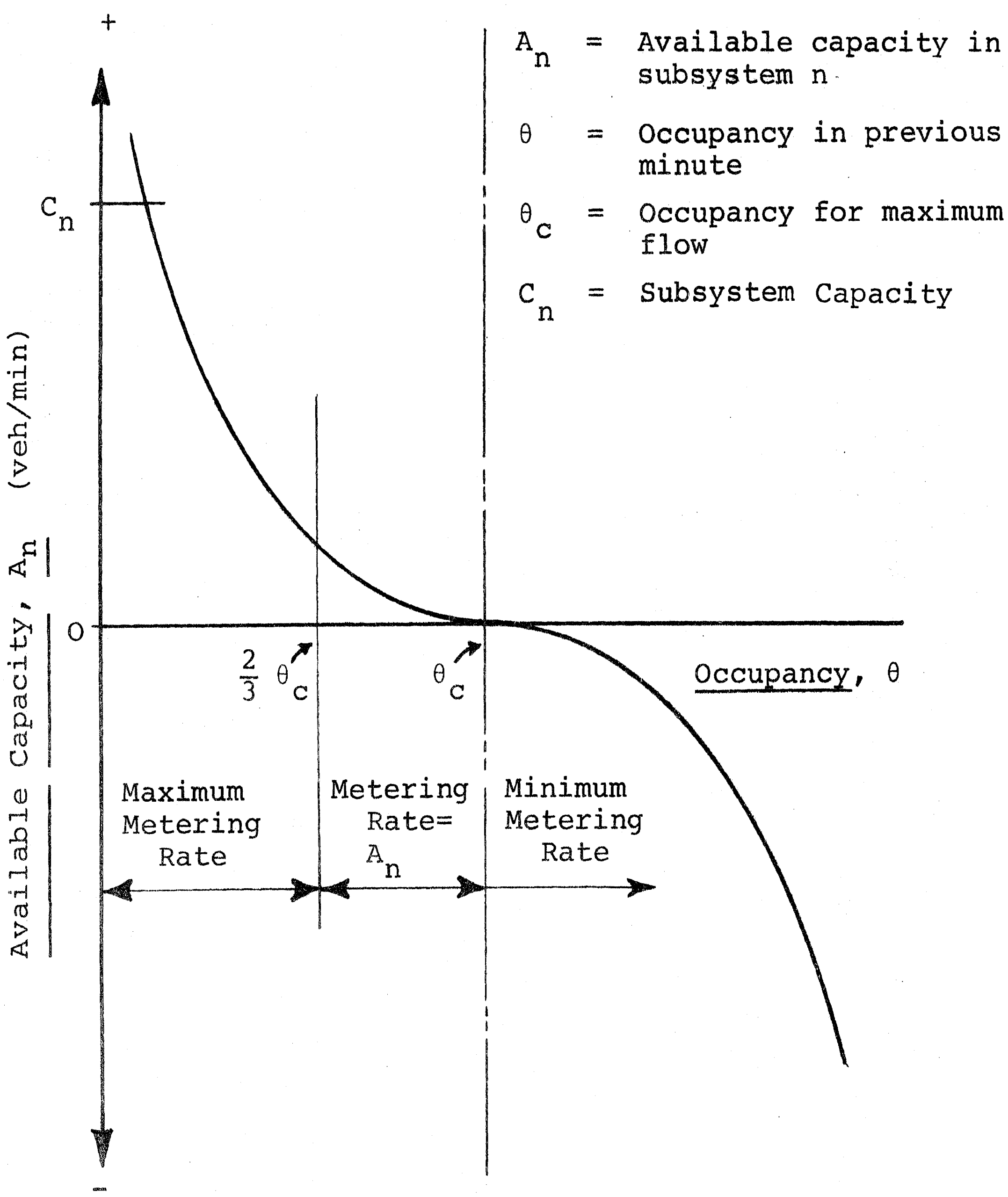


FIGURE 5

PSEUDO REAL-TIME RAMP METERING STRATEGY

This approach of using only one detector station in a subsystem to determine metering rates did not take into account the possibility of an accident or other capacity-reducing incident occurring just upstream of the detector station. In this case, the occupancy at the station would remain low but the high metering rate generated would only increase the congestion building upstream from the incident. The metering rate should be set so that the number of vehicles in the subsystem between detector stations, the storage, does not exceed a critical level. This would also enable the metering rate to be responsive to a sudden increase in flow into the subsystem.

The storage in a subsystem at the end of each minute could be calculated if the number of vehicles within the subsystem at some point in time were known. This initial storage figure could be updated for succeeding minutes by means of measured input volumes to and output volumes from the subsystem. Unfortunately, it was not possible to measure directly the number of vehicles within the subsystem with the sensing system available and a method was devised to provide an estimate of the subsystem storage.

Storage was estimated by dividing the estimated total travel in the subsystem (vehicle-miles per minute) by the average space mean speed (miles per minute). The travel in the subsystem and the average speed were determined from the detector station volumes and occupancies, entrance and exit ramp volumes, and the distances between the ramps within the subsystem. Derivations of the relationships are presented in Appendix A.

Once the storage has been estimated for a given minute it can be updated from the net input or output volume of the subsystem in succeeding minutes as mentioned above, or it can be estimated in succeeding minutes by reapplying the above storage formulas each minute. Consistent with the findings of other studies, it was found that the method based on volume inputs and outputs drifted into error as a result of detector errors. Therefore, a conservative approach was used and at the end of each minute storage values calculated by both methods were compared and the greater value used to calculate the metering rates. The selected storage value was also used for the input-output updating in the next minute. In using the larger estimated storage value the metering strategy attempted to compensate for possible estimate errors by limiting subsystem input more than might be necessary if a better sensing system were available.

For each subsystem there was a predetermined maximum allowable storage. Whenever the calculated storage was greater than this allowable storage value, minimum metering rates were employed. Otherwise, the metering rate was set equal to the difference between the storage estimate and the allowable storage up to the maximum metering rate.

The method of metering was at first changed at only the four upstream ramps (West Grand Boulevard to Webb). Later, as detector stations were added between metered ramps, eventually all ramps with the exception of Livernois West (ramp number 7 in Figure 1) were metered by the same method. The ramp at Livernois West continued to be metered on the original basis using preprogrammed rates. This was because it was of less importance to the system than Livernois East and the new method can independently obtain a rate for only one input ramp per subsystem, which in this case extended from Muirland Avenue to Tuller Avenue.

EFFECTIVENESS OF THE NEW RAMP METERING STRATEGY

To test the improvement obtained from this new method of metering, two sample peak four-hour periods of 19 days before the change and 12 days after its initiation were selected for study. The "before" sample period extended from October 2 to October 30, 1969. During this interval, all equipment operated properly, enabling acquisition of complete freeway volume and occupancy data for each peak period minute, as well as a listing of information sign states. The "after" sample period extended from October 31 to November 31, 12 days. After this date the Edsel Ford detector station was moved and a set of dynamic routing information signs became operational (28).

For each of the 31 days, total freeway travel and total freeway travel time was calculated in a way similar to the minute-by-minute methods used to determine metering rates (Appendix A). First, the values of total travel, occupancy, and volume available for each minute over the four-hour peak period for each subsystem were totaled. Then, overall average speed was calculated for each subsystem by obtaining the quotient of total volume and total occupancy for each station and multiplying by a known constant (Table A-3). Finally, the total travel time for each subsystem, the ratio of total travel to average speed, was summed for the freeway section extending from the Edsel Ford Freeway to Meyers Road. Total travel and total travel time have been plotted in Figure 6 for each of the 31 days.

Six days, three "before" and three "after" the change, were eliminated from further analysis because it is evident that the values of total travel and total travel time do not

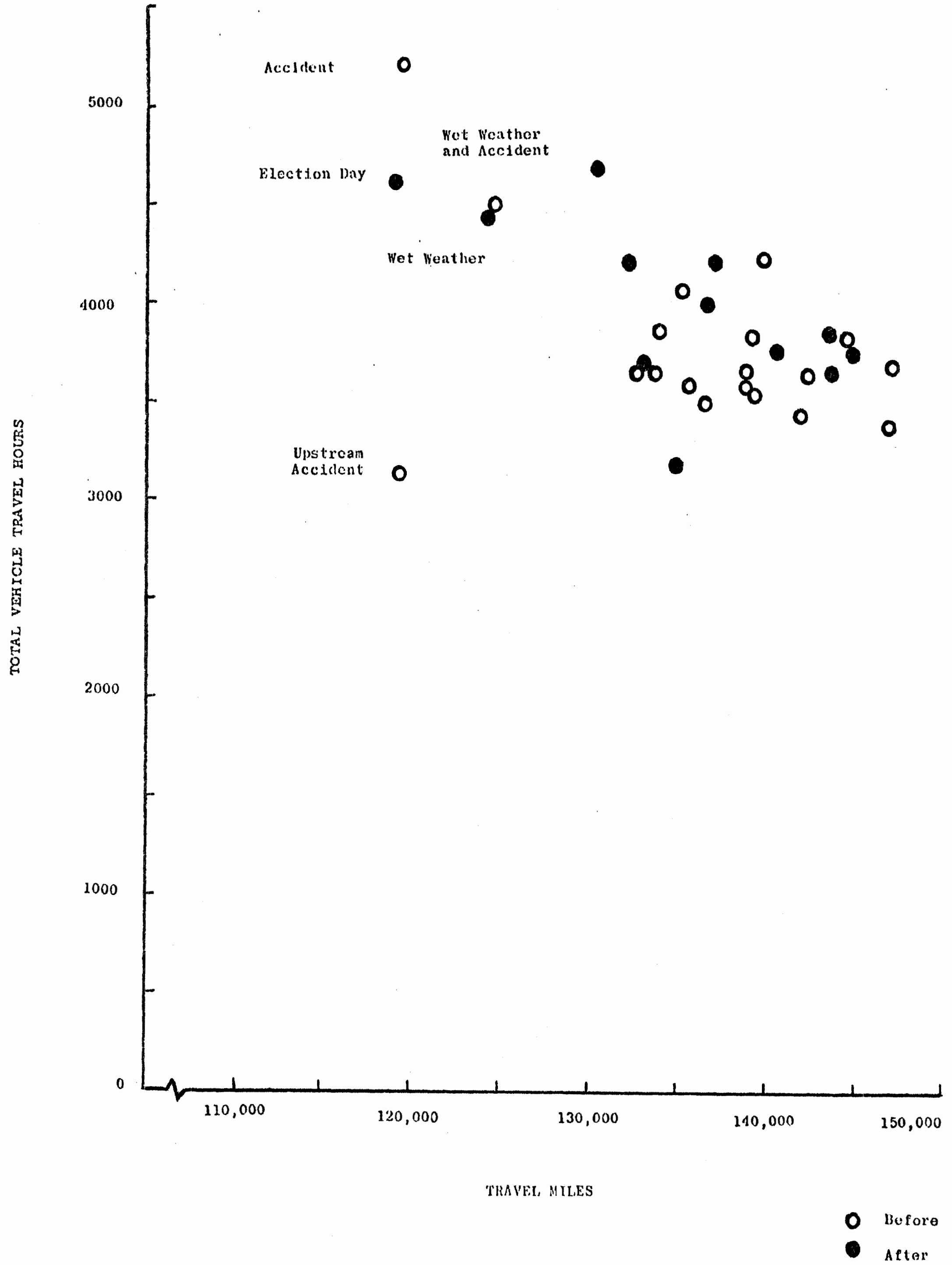


FIGURE 6

EFFECT OF CHANGED RAMP METERING STRATEGY
ON TOTAL TRAVEL AND TOTAL TRAVEL TIME

fit the usual patterns. The likely explanations, holidays or inclement weather, are also shown in the diagram. Although the metering can cope adequately with unusual situations caused by weather or changes in work patterns, these occasions are not sufficiently numerous to permit a rational "before" and "after" comparison.

The remaining 16 "before" days averaged 3,678 total vehicle travel hours and 139,200 travel miles per day. The nine "after" days averaged 138,600 travel miles per day, a slight and insignificant change. The average total vehicle travel hours per day increased to 3,792. This was a more substantial change, but the difference was not statistically significant. Referring to Figure 6, there was a distinct tendency for "after" days to have higher total vehicle travel hours than the "before" days, but it could not be statistically verified. Evidently the freeway congestion regularly present for a considerable portion of the peak period made it unlikely to change total travel or total travel time to any great extent.

It is likely, however, that a saving in travel time can be obtained at on-ramps where queues develop as vehicles wait to enter the freeway. For the same demand to use each ramp, a change in metering methods might result in a lower average service time and, therefore, in less delay for those in the queue. If the demand is different, however, a simple measurement of queuing delay will not necessarily indicate a reduction in service time, as there could be a decrease in the arrival rate.

For the six upstream ramps included in the comparison, the average entering volumes "before" and "after" the modification in the metering strategy are given in Table 1 for the above sample days. The "t" test was used to determine whether the recorded differences were statistically significant.

TABLE 1

COMPARISON OF ENTRANCE RAMP VOLUMES

ENTRANCE RAMP	BEFORE	AFTER	RESULT
West Grand Boulevard	3410	3720	Highly Significant
Seward	925	911	Not Significant
Chicago	914	840	Highly Significant
Webb	858	795	Highly Significant
Davison	4540	4460	Not Significant
Linwood	1233	1430	Highly Significant
TOTAL	11880	12156	

Although the average total volumes changed little for the "before" and "after" periods, there were several significant volume shifts among the ramps. There was a highly significant increase in usage of the West Grand Boulevard ramp. This may be a consequence of there being more available storage in that freeway subsystem as a result of the fourth freeway lane. The lane is used primarily by entering and exiting vehicles. The resulting reduced ramp congestion at West Grand Boulevard may explain the volume reductions at the downstream ramps. Fewer vehicles would be diverted either by the ramp information signs or direct observation of the reduced congestion at West Grand Boulevard. The increase at Linwood may be due to more traffic being diverted by the ramp information signs should it be found that less congestion was present there as a result of the new strategy.

A ramp is defined as congested if the queue occupancy exceeds a preset critical level. The occupancy levels are 35% for Davison and 20% for the other five ramps (9). The computer records include the state of the ramp information signs which indicate red for congestion if the critical ramp occupancy is exceeded and green otherwise (28, 29). The extent of congestion is therefore indicated by the amount of time the signs had red displays over the four-hour period. Since the new method of metering could well be more effective during those parts of the peak period with least demand, the four hours have been divided into single hour periods. The traffic demand is less during the first hour and often less during the last hour. Table 2 gives the average time of congestion (red) during each hour for the periods of study.

At four of the six ramps, West Grand Boulevard, Seward, Webb, and Linwood, there was a decrease in the average ramp congestion period, averaging 10 minutes. At the Chicago and Davison ramps there was an increase averaging nine minutes. In addition, two of the four ramps which experienced a decrease in congestion had an increase in demand. If demand had remained constant, the congestion would have been even less. There was a significant decrease in demand at the Webb ramp, but this decrease was not so large as the increases at Linwood and West Grand Boulevard. The greatly reduced congestion at Linwood appears to explain the evident increase in vehicles diverted there (see Table 1).

For both the "before" and "after" days, the average time ramps are congested increased for all ramps in both the second and third hours and decreased for all ramps in the fourth hour. This increase was significant between the first and second hours for all the ramps and occasionally significant for other periods. It was therefore concluded that

TABLE 2

RAMP CONGESTION
(Minutes)

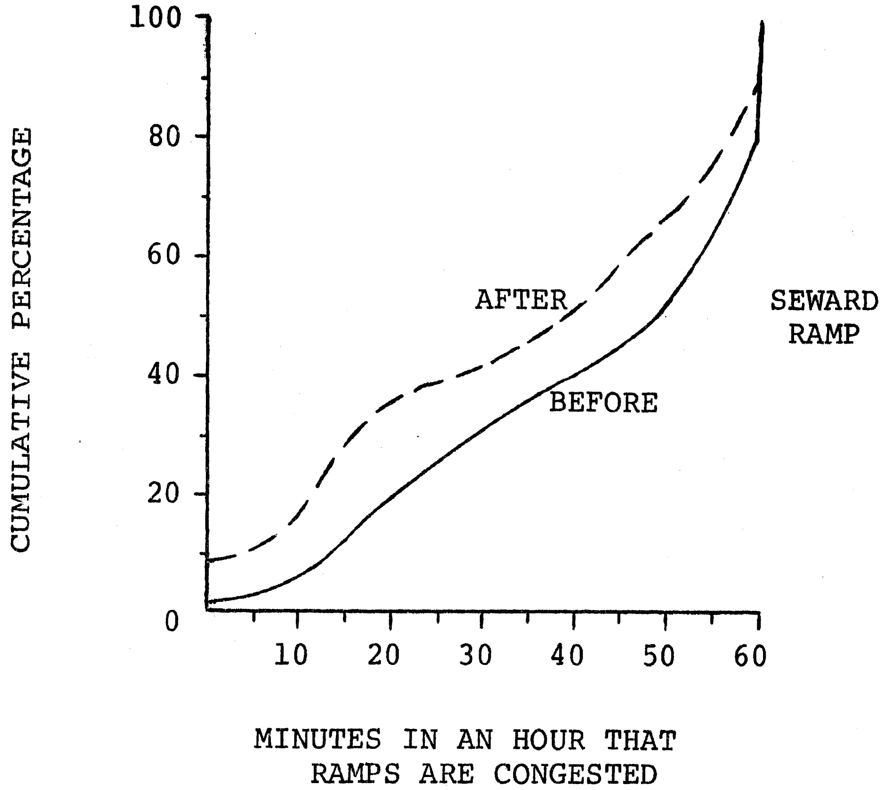
Ramp	State	2:30-3:30	3:30-4:30	4:30-5:30	5:30-6:30	Overall
West Grand Boulevard	Before	32.2	51.5	57.4	28.2	42.3
	After	5.7	23.6	47.3	35.2	28.0
Seward	Before	23.1	49.6	55.3	38.8	41.7
	After	5.7	25.6	55.8	46.1	35.1
Chicago	Before	27.4	51.6	56.4	40.4	43.8
	After	20.3	54.0	58.1	52.7	46.3
Webb	Before	24.8	46.8	58.8	40.9	42.8
	After	17.3	42.6	55.8	48.1	41.0
Davison	Before	9.1	29.1	53.2	24.1	28.8
	After	23.7	45.2	56.0	49.0	44.0
Linwood	Before	4.0	36.4	58.8	48.5	36.9
	After	1.6	16.4	26.0	10.7	16.2

the general pattern of congestion was the same in both the before and after periods. Demand and congestion increased through the third hour of the peak period and slackened somewhat in the fourth hour.

Further inspection revealed definite trends that confirmed the prediction that the new metering strategy would be more effective in the earlier hours of the peak period.

In the first hour of the peak period congestion decreased at five of the six ramps. At West Grand Boulevard and Seward the decreases of 27 and 18 minutes of congestion were statistically significant. In the second hour congestion decreased at four of the ramps, and the decreases of 28 and 24 minutes were again significant for West Grand Boulevard and Seward. In the third hour the congestion changes were mixed and generally insignificant, but in the last hour there were congestion increases in all but one of the ramps. Apparently, the effect of the new metering strategy was to delay the onset of ramp congestion in the earlier hours at the expense of a slower recovery at the end of the peak period. This trend was confirmed statistically by means of a sign test on the "before" and "after" changes. There was also a trend for congestion decreases to occur at the upstream ramps earlier in the peak period, and increases to occur farther downstream and later in time. This further evidence of congestion diversion was confirmed neither at Davison, where congestion increased each hour, nor at Linwood, where it decreased every hour.

Cumulative frequency distributions were compiled for the hourly minutes of ramp congestion for each "before" and "after" hour both for a representative ramp, Seward, and all of the ramps (Figure 7). In both cases there were distinct increases in the proportion of uncongested ramp



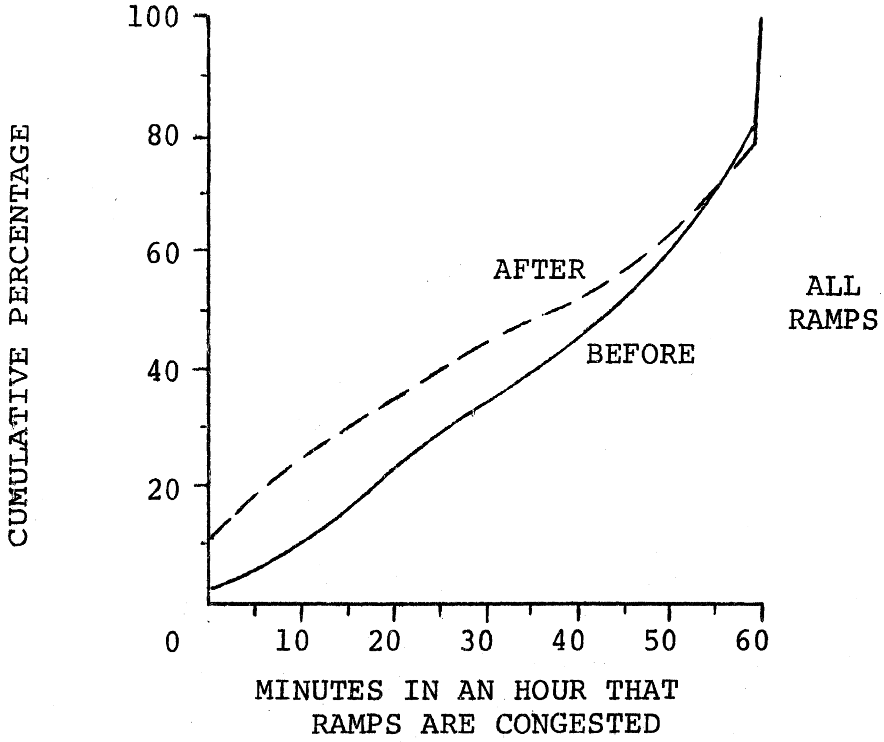


FIGURE 7

CUMULATIVE FREQUENCY DISTRIBUTIONS OF HOURLY RAMP CONGESTION CONDITIONS

conditions, certainly a tangible benefit for the freeway ramp user. It is concluded that the new ramp metering strategy is of greatest benefit in the early hours of the peak period. The principal effect of the strategy is to retard the onset of ramp congestion during the peak period so that overall a smaller portion of the peak period exhibits ramp congestion.

To determine the saving in travel time, it was assumed that a "green" sign state represents a queue of zero length while a "red" state, congestion, represents a queue of maximum length up to the queue detectors. The maximum queue lengths (number of vehicles) were:

West Grand Boulevard	30
Seward	20
Chicago	20
Webb	20
Davison	40
Linwood	20

The number of vehicle hours of delay experienced in a ramp queue is presented in Table 3 and was obtained by multiplying the average "red" time per hour by four and then multiplying this product by the above queue lengths. In the "after" case, a correction was made for different demand by assuming

TABLE 3

DELAY AT METERED RAMPS
(Vehicle Hours)

Ramp	Before Metering Change	Scaled Before	After Metering Change
West Grand Boulevard	84.6	92.4	56.0
Seward	55.7	55.7	46.8
Chicago	58.5	53.6	61.8
Webb	57.0	52.9	54.7
Davison	76.8	76.8	117.5
Linwood	49.2	57.0	21.6
TOTALS	381.8	388.4	358.4

queue length to be proportional to demand. This was a conservative assumption as the rate of increase of queue length increases monotonically with increases in demand. For example, for a single channel queue with random arrivals at rate q and regular service at rate Q, the average number of vehicles in the queuing system is proportional to

$$q/(Q-q)$$

Clearly as q increases N increases at a faster rate. The "before" delay experienced in ramp queues was scaled for the same demand as for the "after" delay.

As a rough estimate, the new method of ramp metering saved an additional 30 vehicle hours per day or approximately 7500 vehicle hours per year. It was not feasible to obtain a cost/effectiveness ratio because there was virtually no cost in installing and operating the system. However, in the TTI report (34), the total annual cost over 10 years was given as $83,000. The estimated effectiveness was given as 902 vehicle hours per day or 225,000 vehicle hours per year. This last amount would be increased to 233,000 vehicle hours on the basis of the improved system. Thus, an improved cost of about 36¢ for every vehicle hour saved was obtained as compared with 37¢ found by TTI.

MODIFICATIONS IN BULK METERING STRATEGY AT DAVISON ENTRANCE RAMP

There were two exceptions to the single service ramp metering strategy. At two high flow ramps, West Grand Boulevard and Davison Freeway, a "bulk service" strategy which allowed more than one vehicle to enter the freeway at a time was used by TTI (34). At both locations, it was highly undesirable that lengthy queues develop because of lack of adequate storage space. At West Grand Boulevard the ramp queues occasionally extended to and through the intersection of the Service Drive and West Grand Boulevard, thus interfering with all movements in that intersection. The problem at the Davison Freeway interchange was potentially more severe. Davison is a freeway and ramp queues could extend into the Davison traveled lanes and even block a nearby on-ramp.

The bulk service ramp metering strategy developed by TTI allowed as many as 13 vehicles to enter during each green phase, with a maximum of 25 vehicles per minute. A 30 second metering cycle was used. After an initial 10 seconds of green time, the signal remained green until 13 vehicles had passed, up to a maximum of 25 seconds. The remaining portion of the cycle, at least five seconds, was allotted to brief amber and red signal phases. The release of a stream of queued vehicles did not necessarily impair merging operations since both entrance ramps led into added freeway lanes of more than 0.5 miles in length.

Despite the use of this high capacity metering strategy, ramp queue length was a problem at both entrance ramps. At West Grand Boulevard it was anticipated that the experimental ramp condition information signs would alleviate the problem by diverting excess ramp traffic and no modifications in the metering strategy were made pending the results of that experiment (29).

The situation at the Davison interchange, however, was critical at the start of the University of Michigan research program. Ramp queues were backing up onto the Davison Freeway to create an intolerable situation in terms of traffic safety. As at West Grand Boulevard, it was anticipated that the later installation of a ramp condition information sign and a variable message sign to divert traffic away from the Davison entrance ramp would be beneficial (28, 29). However, these critical operational problems necessitated the adoption of immediate modifications in the metering strategy to allow the discharge of excessively long ramp queues irrespective of the conditions on the Lodge Freeway.

The alternative of cessation of all metering at the Davison interchange during the peak period was not acceptable. This would have seriously affected the research effort to optimize Lodge Freeway Corridor operations. Therefore, as a first modification of the TTI strategy, it was decided to continue the metering but discharge vehicles at the maximum rate when ramp congestion became critical. A later modification provided for suspension of metering by displaying a constant green indication until the queue was discharged whenever the ramp queue reached a point near the end of the ramp. These strategies were used during the period of peak traffic flow.

To effect these strategy changes, a sonic sidefire detector was installed approximately 300 feet upstream of the metering installation and linked to the control center by a leased telephone line. The detector is shown in the upper right corner of the lower picture in Figure 4. Queue length was determined indirectly from this detector. The detector recorded the occupancy or percentage of time vehicles were passing the detector on a one-minute basis. For example, as the ramp queue neared the detector vehicles had to slow down past the detector thus causing a rise in occupancy. One hundred percent occupancy was recorded when a vehicle was stopped opposite the detector for a full minute. The critical occupancy values cited below were based on observations of occupancy behavior during ramp queues of varying lengths.

The four-hour period of ramp metering was divided into two segments, 2:30 to 4:00 p.m. and 4:00 to 6:30 p.m., and different strategies were applied to each. In the earlier period when freeway operations were not likely to have reached a congested state, the metering rate was set at its maximum to reduce the probability of an excessive ramp queue. In the later period when it was necessary to attempt to maintain lower metering rates to insure satisfactory operations on the Lodge Freeway, certain modifications in strategy were imposed. In the first modification, normal metering rates were maintained until the queue occupancy reached 40%, at which point the rate was set at maximum until the occupancy was reduced. To reinforce the strategy, after their installation the ramp information signs indicated congested ramp conditions when the queue occupancy exceeded 30% in an attempt to divert flow to alternate routes. The red display was maintained for at least two minutes as long as the occupancy remained above 30%.

This strategy was later replaced with a strategy (modification two) that provided for a constant green ramp metering display as needed in order to guarantee that excessive ramp queues would not develop during the first period of metering. The constant green display replaced the maximum metering rate whenever the queue occupancy exceeded 40%. During the 4:00 to 6:30 p.m. portion of the peak period, the following metering rates were applied depending on the occupancy:

$\theta < 35\%$:	Normal metering rates
$35\% \leq \theta < 40\%$:	Maximum metering rates
$\theta \geq 40\%$	Constant green indication

The ramp information sign was operated in the same manner as for the first modification.

Studies of traffic operations at this interchange are summarized in Tables 4 and 5 for one day of operation with maximum metering and two days with suspended metering. For comparison purposes results for an earlier "before" day when the TTI bulk metering strategy was used are included. As would be expected, volumes are consistently lower for the earlier portion of the peak period, but the totals vary from almost 4000 vehicles on May 23 to more than 3800 during July and less than 3200 in June. It appears that the June 20 volumes are just abnormally low, as the metering strategy in effect that day would not be expected

TABLE 4

TRAFFIC VOLUME AT DAVISON ENTRANCE RAMP

	Volume (Total Vehicles) 2:30--4:00 PM	4:00--6:30 PM	Total
TTI Bulk Metering Strategy (May 23, 1969)	1531	2459	3990
Modification One-Maximum Metering (June 20, 1969)	1164	2009	3173
Modification Two-Suspend Metering (July 16 and 25, 1969)	1341**	2478**	3819**

TABLE 5

RAMP METERING STRATEGIES AT DAVISON ENTRANCE RAMP

	Queue Occupancy* (Percent)		Ramp Metering Control State 2:30--4:00 PM		Ramp Metering Control State 4:00--6:30 PM		
	2:30-4:00 PM	4:00-6:30 PM	Maximum Metering (Minutes)	Constant Green (Minutes)	Normal Metering (Minutes)	Maximum Metering (Minutes)	Constant Green (Minutes)
TTI Bulk Metering Strategy (May 23, 1969)	---	---	---	---	150	---	---
Modification One-Maximum Metering (June 20, 1969)	27.4	34.1	90	---	93	57	---
Modification Two-Maximum Metering (July 16 and 25, 1969)	21.6**	28.2**	85.5**	4.5**	105.5**	10.5**	34**

*One minute average during the period
**Average for two days of operation

to affect volume to this extent. Despite handling almost 20% more vehicles in the four-hour period, there was a distinct reduction in average queue occupancy when modification two was employed instead of modification one. This was achieved by suspending the ramp metering for an average of only 38.5 minutes per day.

During the 2:30 to 4:00 p.m. period, there was little difference in the operation of the two modified control strategies. The constant green state was only imposed an average of 4.5 minutes during this period for the second control modification.

During the latter period from 4:00 to 6:30 p.m., the advantage of the constant green state became apparent. The first modification resulted in 93 minutes of normal metering and 57 minutes of maximum metering. During the period of operation of the second modification, however, the number of minutes of normal operation was increased to 105.5 minutes (104 and 107 minutes for the two days studied). Thirty-four minutes were devoted to constant green, the constant green time being imposed for an average duration of two minutes. Thus, the use of the constant green time, though undesirable in terms of corridor operations, did result in more metering time spent with the rates determined by conditions on the Lodge Freeway.

The study indicated that the use of the steady green indication allowed the correction of excessive ramp congestion. An excessive queue could promptly be discharged so that normal metering strategy could again be used. Further investigation of the Davison situation and the impact of the variable message sign placed there is described in another report (28).

ENVIRONMENTAL EFFECTS ON FREEWAY TRAFFIC OPERATIONS

Since the metering rate within each freeway subsystem was based on "available capacity," the fixed pre-determined value for subsystem capacity was vital to effective operation. Should this capacity value not be representative of actual freeway conditions, the metering program would be rendered less effective and the surveillance program in general would not have the flexibility needed to meet changed conditions. Impaired visibility because of precipitation and consequent slippery pavement conditions both would be expected to have an effect on vehicular headways and speeds with resultant effects on capacity.

In a preliminary study of these effects at four freeway sensing stations, two representative days of clear, dry conditions and two days of wet pavement were selected. One minute average flow characteristics as measured at the sensing stations for four hours were assumed to follow a deterministic relationship so that such parameters as theoretical capacity and free speed could be derived from the data. These parameters were then compared to determine if any significant differences could be ascribed to the occurrence of rainfall.

Thus, 240 one-minute volumes were plotted against occupancy for each of the four days. Since it has been shown that occupancy is generally proportional to density, a change of scale is all that is necessary to convert this plot to one of volume against density (9, 26). In order that these results could be compared with those obtained by others, a parabolic relationship between volume and occupancy based on the Greenshields' relationship as shown below was fitted to the data (14). The data were also fitted to a logarithmic function of k.

$$q = k\, u_f\, (1 - k/k_j)$$

where u_f is the free speed (speed at zero volume)

k_j is the jam density

Then capacity, q_c, in this relationship is

$$q_c = \frac{1}{4}\, u_f\, k_j\ .$$

A least squares parabola was fitted to the data. Capacity was taken as being equal to the maximum volume corresponding to the vertex of the curve. Since total freeway demand was at times sufficient to exceed capacity, this method was suitable.

The four consecutive freeway sensing sites employed to gather the volume and occupancy data are designated Freeway Stations 2, 3, 4, and 5. Station 2 (which is at Seward) has four northbound lanes while the other stations (at Chicago, at Calvert between Chicago and Webb, and at Glendale (see Figure 1)) have three northbound lanes. There are no unusual geometric design features over this reach of freeway, although Station 3 is located midway through a reverse curve.

Table 6 lists the fitted capacity values recorded for each of the stations for each of the four days.

TABLE 6

FREEWAY STATION CAPACITY
(Vehicles/Minute)

DATE 1969	WET OR DRY	STATION NUMBER			
		2	3	4	5
OCT 7	WET	105	82	93	103
OCT 10		97	85	89	91
OCT 8	DRY	117	87	93	93
OCT 28		96	83	85	92

In this limited study of four days' data, it was not possible to show any differences in the relationship between volume and occupancy under differing weather conditions. It was shown that there was an inconsistency among data for the four stations on any two days. It is possible that the inclusion of data from other days, together with a recalibration of the proportional constants between density and occupancy, and even the use of other relationships between volume and density may show wet pavement to have an effect on freeway operations.

CHAPTER FOUR

RAMP METERING AND ACCIDENT EXPERIENCE

Studies made in Chicago, Houston and Atlanta have shown a substantial decrease in accident experience, particularly rear-end accident occurrence, following the installation of ramp metering (17, 19, 30, 32). Total ramp, freeway and frontage road accidents were halved in Houston and rear-end ramp accidents cut 90% in Atlanta. Hence, there was reason to believe that the introduction of ramp metering in Detroit would be reflected in a reduced accident rate on the freeway. One possible outcome of control of freeway operations might be safer merging at entrance ramps since ramp metering would serve to make more orderly the introduction of vehicles and to reduce the rate of input when freeway volumes were high. It was also necessary to investigate the potentially adverse effect on the accident rate in terms of rear-end collisions on the entrance ramps because of the presence of metering. It would also be of interest to see if the accident response to metering would change with time as motorists became accustomed to the different mode of merging. The existence of a continuous ramp metering program on the John C. Lodge Freeway from July 1967 through 1969 and later made an accident analysis possible for this six-mile section of freeway.

The first studies of accident experience on the Lodge Freeway were reported by Crane who studied accidents on four ramps and the nearby service roads in the Lodge Freeway Corridor (10). His data show that while accident frequency remained stable during the hours that there was no ramp metering, following the introduction of metering there was a large increase (significant at the 5 percent level) in accident occurrence during ramp-metering hours as shown in the following tabulation:

	NUMBER OF ACCIDENTS	
	6 Months Before Metering	18 Months After Metering
During Metering Hours	2	38
During Other Hours	9	23

He observed that this increase was largely due to the effect of the bulk-service ramp metering at the West Grand Boulevard where 24 of the 38 accidents occurring during ramp metering happened. While this increase was predominant, the increase on the three single-service ramps was also disappointing as shown in the following tabulation:

	6 Months Before	18 Months After
During Metering Hours	1	14
During Other Hours	9	19

These results, while not statistically significant, indicate a negative effect of ramp metering of these locations that deserves additional study.

STUDY TECHNIQUE

In order to study these effects, a representative period before the introduction of ramp metering and computer surveillance control was compared with the same part of the year for the two years following installation of ramp metering. The last quarter of the year (October 1-December 31) was selected because of data comparability problems. Data for 1966 provided a basis for comparison with accident experience during 1967 and 1968. The ramp metering was made operational in early July 1967. Since only weekday freeway traffic during the peak period of 2:30 p.m. to 6:30 p.m. was affected by the ramp metering operation, only accidents which happened in that time period were considered in the "before" and "after" comparisons.

These accident data, obtained through the surveillance system on the freeway and from the City of Detroit on the entrance ramps, were categorized by type of collision (rear-end, side-swipe, or other), severity (personal injury or property damage) and pavement condition (dry, wet, or slippery).

The Chi-square test was used to compare the "before" with the two "after" periods for statistical significance. A five percent level for errors of the first kind was used to establish statistical significance.

RAMP ACCIDENTS

Table 7 presents a summary of accident experience during the three study periods for both the peak period and all other times of day (off-peak). The type of accident is not shown since all accidents occurring on the entrance ramps were of the rear-end type. There were three peak period accidents on the eight ramps studied during 1966, nine in 1967, and three in 1968, a total of 15. There was a total of 23 accidents during the three off-peak periods.

The data on accident experience on the entrance ramps for the three years were analyzed by use of the Chi-square test. It is noted from Table 7 that there were more accidents in each of the two "after" periods (1967 and 1968) than in 1966, a difference as great as 6 accidents. This increase was recorded both during the period of ramp metering as well as during the other hours of the day. Even these differences could easily be due to chance. It is clear that in considering the average of the two "after" periods, there is no reason to believe that the introduction of ramp

TABLE 7

ACCIDENT EXPERIENCE ON ENTRANCE RAMPS

YEAR	PERIOD	CONDITIONS		SEVERITY		TOTAL
		WET OR ICY	DRY	PERSONAL INJURY	PROPERTY DAMAGE	
1966	Peak*	3	0	1	2	3
	Off Peak	2	2	3	1	4
1967	Peak	4	5	5	4	9
	Off Peak	4	6	3	7	10
1968	Peak	0	3	3	0	3
	Off Peak	3	6	2	7	9

*Peak period from 2:30 P.M. to 6:30 P.M. on Weekdays

Data for October, November, and December of Each Year

metering effected a change in accidents experienced on the entrance ramps. Further examination of the data indicate that there was a substantial decrease in accidents during the peak period on the ramp during the second year of operation, a result consistent with the hypothesis that familiarity with ramp metering systems ultimately results in reduced accident experience. It was not possible to accept this hypothesis with the size of sample available and a conclusion that there is a reduction in accidents in the second year after metering as contrasted with the experience during the first year must await further studies.

Again, the sample is so small that it is impossible to make a strong statement with regard to the relative severity of accidents in response to the ramp metering. However, it is noted that there is a possible trend for the severity of peak-period ramp accidents to involve personal injuries more often than accidents occurring at other times.

An analysis of the effects of pavement condition indicated no identifiable or statistically significant effects of ramp metering.

FREEWAY ACCIDENTS

A similar analysis was made to determine if the ramp metering system affects the occurrence of on-freeway accidents. The presence of ramp metering in 1967 could have had a beneficial effect on vehicle merging downstream of ramps, thereby reducing the potential for disturbances in traffic operations that could generate accidents. In 1968 digital computer control of freeway operations was introduced to minimize total travel times on the freeway through ramp diversion and reduction of congestion on the freeway. Smoother traffic operations might be reflected in fewer on-freeway accidents.

The data for on-freeway accident experience for the 1966, 1967, and 1968 quarters are shown in Table 8. An analysis of total accident occurrence on the freeway showed that there was no significant change in the total accident experience during the three years. While the number of accidents during off-peak hours varied little, 28, 27, and 29, there were 21 peak-hour accidents in 1966, 14 in 1967 (a 33.3% reduction), and 18 in 1968 (a reduction of 14.3% from 1966). A Chi-square test was made to determine whether this apparent decrease in the number of peak-hour accidents in 1967 and 1968 following metering was significantly lower when considering the fact that the off-peak accident

TABLE 8

ON-FREEWAY ACCIDENT EXPERIENCE

YEAR	PERIOD	CONDITIONS		COLLISION TYPE			SEVERITY		TOTAL
		WET OR ICY	DRY	REAR END	SIDE SWIPE	OTHER	PERSONAL INJURY	PROPERTY DAMAGE	
1966	Peak*	6	15	18	1	2	9	12	21
	Off Peak	7	21	22	6	0	9	19	28
1967	Peak	4	10	11	3	0	5	9	14
	Off Peak	14	13	14	12	1	9	18	27
1968	Peak	3	15	11	6	1	7	11	18
	Off Peak	9	20	18	6	5	11	18	29

*Peak Period from 2:30 P.M. to 6:30 P.M. on Weekdays

Data for October, November, and December of Each Year

experience remained essentially similar. The 25% reduction in on-freeway accident experience is not statistically significant and a substantially larger sample would be necessary to support such a contention. Possibly future results will become available that can be used to support such a finding.

An analysis of the severity of freeway accidents as indicated by the frequency of personal injury and property damage accidents indicated that there was neither a significant difference between peak and off-peak severity, nor a significant indication of any difference in severity as a result of ramp metering.

The majority of on-freeway accidents are of the rear-end type, reflecting the greater opportunity for these accidents as a result of acceleration and deceleration waves in congested traffic. There were fewer peak period rear-end collisions after implementation of ramp metering, but off-peak rear-end accidents also decreased.

A statistical analysis of the type of collision, rear-end or other types, again indicated no statistically significant difference between peak and off-peak periods or between the "before" ramp metering and "after" ramp metering periods. Also, an analysis of pavement conditions for peak and off-peak periods and for "before" and "after" metering did not indicate any statistically significant difference or any trend that would be worth reporting.

TOTAL ACCIDENTS

Total freeway accident experience, including ramp accidents, is presented in Table 9. There was no significant change in the total number of accidents occurring each year. Examination of the total number of freeway accidents, including ramp accidents, revealed a slight decrease (10%) during the peak period in 1967 and 1968. As off-peak accidents increased almost 20% there is an indication that freeway surveillance has been beneficial in reducing accidents on the freeway and affected metered ramps. However, a Chi-square test showed that a much larger sample would be necessary to confirm such a conclusion.

No significant differences in pavement conditions, collision type or severity appears to be associated with the introduction in ramp metering.

TABLE 9

TOTAL FREEWAY ACCIDENT EXPERIENCE

		CONDITIONS		COLLISION TYPE		SEVERITY		
YEAR	PERIOD	WET OR ICY	DRY	REAR END	OTHER	PERSONAL INJURY	PROPERTY DAMAGE	TOTAL
1966	Peak*	9	15	21	3	10	14	24
	Off Peak	9	23	26	6	12	20	32
1967	Peak	8	15	20	3	10	13	23
	Off Peak	18	19	24	13	12	25	37
1968	Peak	3	18	14	7	10	11	21
	Off Peak	12	26	27	11	13	25	38

*Peak Period from 2:30 P.M. to 6:30 P.M. on Weekdays

Data for October, November, and December of Each Year

CHAPTER FIVE

INTERPRETATION AND APPRAISAL OF FINDINGS

DESIGN OF A COMPLETE RAMP METERING INSTALLATION

It is evident from the reduction in the violation rate when explanatory devices are installed that the driver's understanding of the concept and proper operation of ramp metering cannot be taken for granted. Drivers treat the isolated signal head as they would any traffic signal and by running the amber light generate violations. Since some ramps on the Lodge Freeway in Detroit allow more than one vehicle to pass through on the green-amber phase, it cannot be assumed that drivers instinctively understand the one-vehicle-at-a-time metering on the other ramps.

The installation of ramp metering devices on a single-service ramp should therefore include an explanatory sign similar to the "ON GREEN ONE CAR ONLY" employed in this research. Such a sign facilitates enforcement by insuring that the driver knows what is expected. The signal head need not contain an amber signal since all vehicles must stop at the signal. A stop bar adjacent to the signal is desirable to emphasize the process and help prevent the possibility of vehicles stopping outside the loop detector that activates the signal. Should the ramp be of sufficient width to allow two vehicles abreast, longitudinal pavement markings that delineate a single lane have been shown to be beneficial. It may be desirable to reinforce these markings with raised markers. Finally, a warning sign at the head of the ramp indicating the presence of ramp metering is considered good traffic engineering practice. It may prevent rear-end collisions with stopped vehicles on the ramp by drivers unfamiliar with ramp metering or not fully alert to its presence.

The accident analyses presented in this report demonstrate that accidents on entrance ramps deserve serious consideration. Unlike the experience in other cities with metering installations, the number of accidents on the metered Lodge ramps increased although not significantly. Studies by Crane on the Lodge Freeway confirmed these results and indicated significant increases in accidents at one bulk-metered ramp, West Grand Boulevard (10). There is a greater potential for rear-end accidents here and at Davison since the ramp queues move farther and faster during each signal cycle than at single-service ramps and all vehicles are not expected to stop. Since it is assumed that the vast majority of ramp users at West Grand Boulevard are aware of metering operations either through frequent use or the presence of a warning sign and the ramp information sign, it is possible that improved designs are appropriate for future metering installations.

Considering the problems encountered with getting drivers to pull close enough to the metering installation to register with the presence detector, it is noted that Michigan regulations, and those of many other states, require traffic signals to be over the traveled sections of the roadway. The ramp signals in this study, of course, were at the side of the ramp. It is evident that overhead placement would compound the detection problem since there is no natural stopping point for a ramp driver as at an intersection. The Lodge entrance ramps are on downgrades, and overhead signals conceivably could induce some drivers to stop as far back as the head of the ramp. Where regulations do exist on the placement of traffic signals, it is advisable that exceptions be made for ramp signals to allow the sort of installation used in this research.

APPRAISAL OF RAMP METERING BASED ON FREEWAY STORAGE

The method of ramp metering described in this report is still subject to improvement. The method relies on the calculated storage which is based on the calculated total travel and the average speed between detector stations. The total travel is probably quite accurate as its value depends only on the volumes at the detectors which are known to be quite reliable. However, the value of average speed is less certain. The average speed at the two extremities of a freeway section was used as an estimator of the speeds of all vehicles within the section. A bias will be introduced if there is any tendency for vehicles to slow down as they reach merging areas.

Another procedure which needs further consideration is the use of the storage value derived in the previous minute as the criterion of the number of vehicles to be metered in the next minute. There cannot be an instantaneous response by the metered vehicles. In fact, the last vehicle per minute will enter just before the end of the minute and by this time the situation could have changed.

No consideration is given to the number of vehicles on the surface streets or on the ramps which intend to enter the freeway. If the surface street vehicles are delayed in ramp queues or diverted to downstream ramps via slower surface streets, their travel time in the corridor has most probably not been minimal. This quantity, however, may have been even greater had the vehicles directly entered the freeway where all other vehicles would have had their travel times increased.

Two studies were performed to increase the flexibility of the metering strategies. At Davison, where the entrance ramp linked two freeways, ramp congestion was intolerable since there was insufficient storage available for the ramp queue. The imposition of a temporary constant green indication demonstrated that such congestion could be handled and regular metering operations resumed for the majority of the time during the peak period.

It would also be desirable to take weather factors into consideration if it could be found that they affect traffic operations on the freeway. However, the study contained in this report comparing rainy weather with clear conditions was inconclusive. No significant changes in capacity or free speed on the freeway were detected. The result indicated the need for a larger sample size.

CHAPTER SIX

CONCLUSIONS AND SUGGESTED RESEARCH

Ramp metering does not encourage a natural traffic maneuver in that it requires vehicles to stop along the entrance acceleration ramps to freeways. Also, it cannot be assumed that drivers understand the rationale behind single vehicle metering and thus obey the signal. A ramp metering installation is consequently not complete without both a warning sign and an explanatory sign. Very few drivers intentionally ignore the ramp signal; rather violations are the result of a second vehicle passing through on the amber phase of the signal close behind the first vehicle. Removal of the amber aspect and the use of an added detector immediately downstream of the ramp signal to terminate the green indication upon passage of the first vehicle decreased the contribution of the traffic control system to violations. The above modifications reduced the frequency of violation from 40% to 10%. While violations are never desirable in terms of driver respect for the installations and the need to restrict inputs to the freeway when congested, this level of disobedience is low enough to render the use of ramp metering effective for controlling freeway corridor operations.

Several modifications to the ramp metering control strategy developed by the Texas Transportation Institute were made in this study. The demand-capacity strategy was replaced by a strategy based on maintaining the storage in a freeway subsystem within acceptable limits. Theoretically, the new strategy provided the capability for a more flexible and precise response to accidents and other capacity-reducing incidents occurring within the subsystem. The new strategy reduced travel time by 30 vehicle hours per day compared to the previous operation of the metering system. This was accomplished by the reduction of delay at the entrance ramps. The new strategy resulted in ramp congestion for a smaller proportion of the peak period. Freeway operations in terms of total travel time were unaffected by the new strategy.

A severe congestion problem was present at the Davison Expressway entrance ramp to the northbound Lodge Freeway. Since ramp queues occasionally extended into the traveled way on Davison despite the use of a high capacity metering strategy, it was necessary to suspend metering operations at times in order to discharge the queue. Rather than terminate metering, a constant green indication was used when congestion was critical. Although undesirable from the point of view of optimizing freeway operations, it was found that ramp congestion could be cleared promptly with the constant green with the result that more of the peak period was spent with the metering strategy determined by freeway conditions.

Since the function of ramp metering is to improve freeway operations by preventing the development of congestion or counteracting the effects of congestion, it was reasonable to expect that freeway accidents would occur less frequently during ramp metering operations. A decrease in freeway accidents, including entrance ramp accidents, of 10% was observed but this was not statistically significant because of the small sample size. However, there was an increase in accidents on the ramps which again because of insufficient sample size could not be statistically confirmed. This contradicts the accident experience in other cities with ramp metering control.

FURTHER RESEARCH

Longer term evaluation of operational metered ramps is desirable to determine if familiarity with the concept or the knowledge that the metering is enforced by the police has any further effect on reducing violations. In this sense, it would be of interest to periodically sample drivers' attitudes toward metering, particularly to measure their awareness of the benefits to be derived from metering in terms of corridor operations.

Another long term study that should be conducted at ramp metered installations is a further examination of the accident experience. The accident studies included in this report were inconclusive in detecting changes in both entrance ramp and on freeway accidents. Should there be a significant increase in accidents on ramps after installation of metering despite the presence of a warning sign, the Detroit installation should be re-evaluated.

More extensive studies of the impact of computer surveillance and control of freeway operations on accident rates are in order. Various control measures were introduced at different points in time, making it difficult to isolate individual effects or provide adequate accumulations of accident data for statistical analysis. One way of avoiding the latter problem would be the analysis of "accident hazard" as a function of traffic turbulence (acceleration noise) resulting from congestion. Significant improvements here, as measured from field studies, could lead to the general conclusion that surveillance operations tend to reduce the potential for accidents.

As indicated in Chapter 5, further improvements in the ramp metering control strategy are possible. There are several weaknesses in the approach developed in this report. The storage estimates need to be verified by independent and accurate methods such as aerial surveys. The metering strategy remains oriented to conditions in single subsystems, although some subsystem interaction is present. Nor do the metering rate calculations take into account surface street traffic. Further research may demonstrate methods for greater integration of ramp metering into freeway corridor operations control. The experience at the Davison entrance ramp suggests the question as to whether ramp queue length should be considered when calculating metering rates.

The metering rate for the next minute is based on traffic conditions in the previous minute. Experience has shown that this could be improved. Possibly the previous data on volume and speed could be averaged over a longer period and could take into account average values for a particular time on a particular day.

The environmental studies included in this report should be considered preliminary as the problem of the physical effects of adverse weather is quite complex and requires additional investigation. Freeway operations are affected when it becomes necessary for some drivers to reduce speed and/or increase headways in order to maintain vehicular stability and to keep their driving task at a reasonable level of complexity. The former is a function of the condition of the pavement surface; while the latter is more complex, since it is primarily a result of impaired visibility.

A previous analysis of on-freeway accidents by DeRose did indicate that environmental conditions are significant in the accident rate[1]. The weather conditions need to be studied so that levels of precipitation can be correlated with traffic operations.

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PART TWO

APPENDIX A

RAMP METERING STRATEGY

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RAMP METERING STRATEGY

The ramp metering strategy developed by The University of Michigan in 1969 incorporates a constraining parameter not previously employed; subsystem length. The basic control premise is that in a given subsystem there exists a maximum available storage, S_m , subject to upstream constraints. If the actual storage were known for a given minute, then the allowable input to the subsystem (the metering rate) would be the difference between these two values. Storage is defined as the number of vehicles contained within the subsystem. Since storage cannot directly be measured, alternative methods were developed for estimating it with the available detector inputs of volume and occupancy.

The total travel time over any time period is the integral of the number of vehicles stored over that period. Expressing total travel time in units of vehicle-minutes, then the storage for a one-minute period is determined from the derivative of the total travel time, or total travel divided by the average speed for the subsystem. The derivation of formulas to estimate total travel and speed are presented below. The following standard notations apply throughout.

S = storage, the number of vehicles contained within the subsystem

$$S = \frac{TT}{\bar{u}}$$

TT = total travel in the subsystem (vehicle-miles per minute)

$\bar{u}$ = space average speed in the subsystem (miles per minute)

The following notations are illustrated in Figure A-1. Subsystem flow inputs are given a positive sign, and outputs a negative sign.

q_1 = on-freeway input volume (vehicles per minute) to the subsystem

$q_2 \ldots q_n$ = on-ramp and off-ramp volumes

q_{n+1} = output volume from the subsystem

E = net subsystem volume or storage change (vehicles per minute):

$$E = \sum_{i=1}^{n+1} q_i = \left(\sum_{i=1}^{n} q_i\right) + q_{n+1}$$

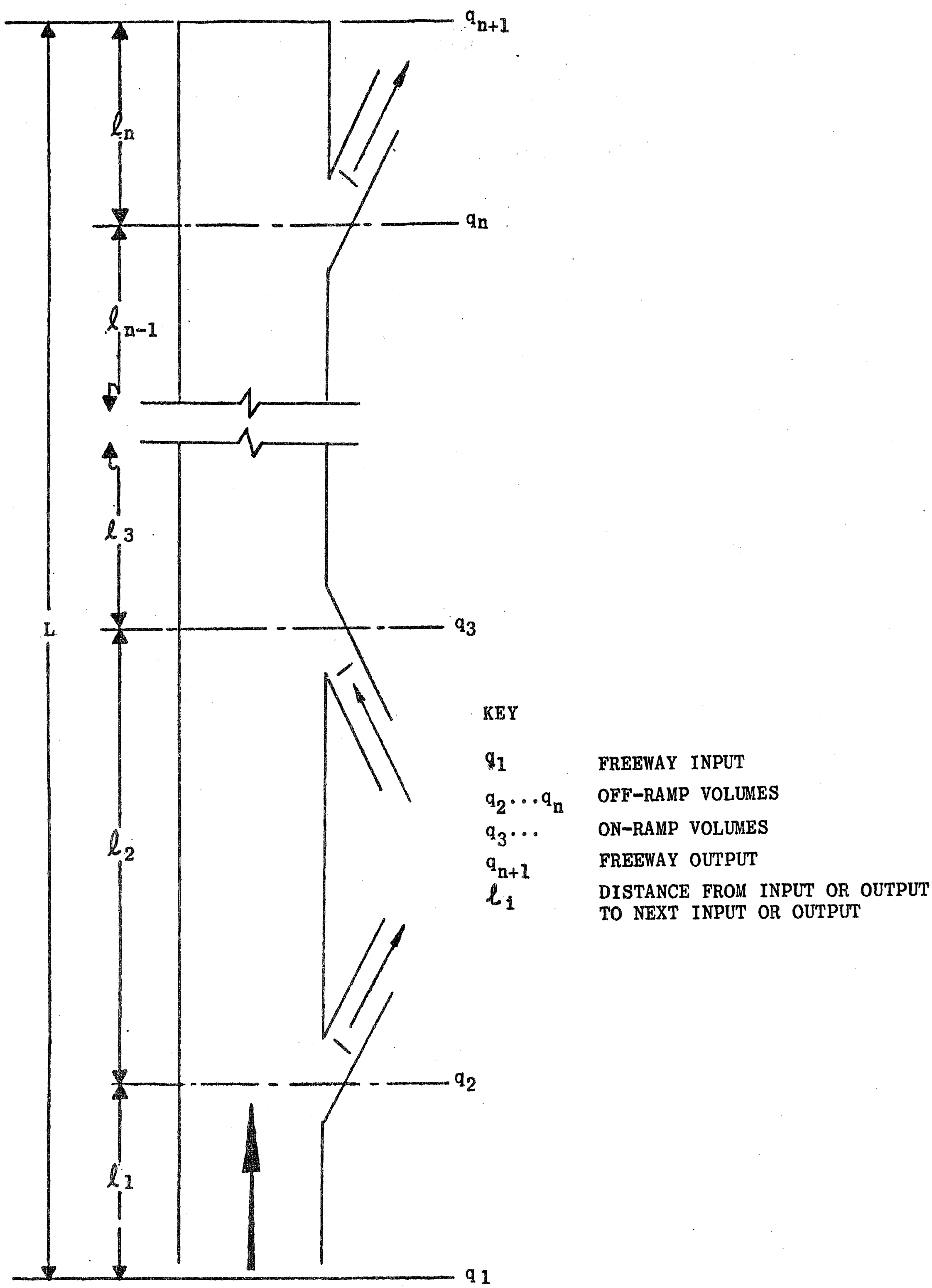

FIGURE A-1

ON-RAMP AND OFF-RAMP LOCATION
FOR TYPICAL FREEWAY SUBSYSTEM

θ_1, θ_{n+1} = percent occupancy (average per one-minute interval) at stations 1 and n+1 of the subsystem

L = total length of subsystem (feet)

l_i = distance from point i to point i+1 in the subsystem (feet)

The lengths of the subsystems in this study are presented in Table A-1. Data on the distances between exit and entrance ramps along the freeway are presented in Table A-2.

Derivation of Total Travel (TT):

Total travel during the one minute of observation is defined as the average travel computed from both ends of the subsystem by the following equation:

$$TT = \frac{1}{2}\left[\sum_{i=1}^{n}\left(l_i \sum_{j=1}^{i} q_j\right) - \sum_{i=1}^{n}\left(l_{n+1-i} \sum_{j=1}^{i} q_{n+2-j}\right)\right]$$

This equation can also be expressed as follows and then converted into a computationally simpler equation:

TABLE A-1

LENGTHS OF SUBSYSTEMS FOR RAMP METERING STRATEGY

Edsel Ford to Seward	4,440 Feet
Seward to Chicago	4,815 Feet
Chicago to Calvert	1,460 Feet
Calvert to Glendale	4,335 Feet
Glendale to Oakman	3,440 Feet
Oakman to Muirland	5,110 Feet
Muirland to Tuller	3,750 Feet
Tuller to Mayers	7,470 Feet
Total Length	34,820 Feet
Edsel Ford to West Grand Boulevard On-Ramp	3,500 Feet

TABLE A-2

NORTHBOUND LODGE FREEWAY ON-RAMP TO OFF-RAMP LENGTHS
(HUNDREDS OF FEET)

	ON-RAMP								
	West Grand Boulevard	Seward	Chicago	Webb	Davison	Linwood	Livernois (1)	Livernois (2)	Wyoming
OFF-RAMP									
Clairmount	34	18							
Chicago	43	27							
Webb	81	65	16						
Glendale	110	94	45	19					
E. Davison	121	105	56	30					
W. Davison	132	116	67	41					
Linwood	177	161	112	86	42				
Livernois	211	195	146	120	76	19			
Wyoming	264	248	199	173	129	72	49	35	
Meyers	303	287	238	212	168	111	88	74	26
Meyers Road	313	297	248	222	178	121	98	84	36

$$TT = \frac{1}{2} \sum_{i=1}^{n} l_i \left(\sum_{j=1}^{i} q_j - \sum_{j=i+1}^{n+1} q_j \right)$$

$$= \frac{1}{2} \sum_{i=1}^{n} l_i \left(\sum_{j=1}^{i} q_j - \sum_{j=i+1}^{n} q_j - q_{n+1} \right)$$

$$= \frac{1}{2} \sum_{i=1}^{n} l_i \left(\sum_{j=1}^{i} q_j - \sum_{j=i+1}^{n} q_j - (E - \sum_{j=1}^{n} q_j) \right)$$

$$= \frac{1}{2} \sum_{i=1}^{n} l_i \left(\sum_{j=1}^{i} q_j + (\sum_{j=1}^{n} q_j - \sum_{j=i+1}^{n} q_j) - E \right)$$

$$= \frac{1}{2} \sum_{i=1}^{n} l_i \left(\sum_{j=1}^{i} q_j + \sum_{j=1}^{i} q_j \right) - \frac{1}{2} \sum_{i=1}^{n} l_i E$$

and

$$TT = \sum_{i=1}^{n} l_i \sum_{j=1}^{i} q_j - \frac{EL}{2}$$

Derivation of Average Speed:

The estimated average speed in the subsystem is taken as the arithmetic average of the mean speeds at each end of the subsystem. Since occupancy has been found to be approximately linearly related to density, the speed at a detector station is proportional to the flow past the station divided by the occupancy for the one-minute interval of observation (9). Thus, the mean speed at the upstream and downstream stations of the subsystem is determined from the following equations:

$$u_1 = p_1 \frac{q_1}{\theta_1} \qquad u_{n+1} = p_{n+1} \frac{q_{n+1}}{\theta_{n+1}}$$

The proportionality constants, p_i, are different for each station owing to differing detector and flow characteristics. The empirically derived constants are listed in Table A-3.

The average speed over the subsystem is then estimated from the following equation:

$$\bar{u} = \frac{1}{2} (u_1 + u_{n+1})$$

Ramp Metering Strategy:

The estimated storage for a given minute is found by dividing the total travel in the subsystem in that minute by the average subsystem speed by means of the equations developed above. In succeeding minutes, storage can be found either by using the above procedure for recomputing the storage or by updating the initial storage value as vehicles enter and leave the subsystem. The change in storage for the ith minute, E_i, is the sum of the vehicle inputs to and outputs from the subsystem. The storage at the end of the kth minute is found from the following recursive relation:

$$S_k = S_o + \sum_{i=1}^{k} E_i$$

TABLE A-3

PROPORTIONALITY CONSTANTS, p, FOR RELATING
FLOW AND OCCUPANCY TO MEAN SPEED
AT EACH DETECTOR STATION

Seward	0.0935
Chicago	0.1993
Calvert	0.1348
Glendale	0.1256
Oakman	0.1763
Muirland	0.2183
Tuller	0.2183
Meyers	0.1763

It was found that the updated storage based on inputs and outputs tended to accumulate errors from the detectors. The initial storage estimate is also assumed to be somewhat in error. Thus, neither method for determining the storage in a given minute can be considered exact. Consequently, at the end of each minute storage was estimated both from estimated total travel and speed in that minute and by updating the storage estimate from the previous minute based on inputs and outputs. The greater of the two storage estimates was used as the storage value for that minute, resulting in more stringent ramp metering than was perhaps necessary. This storage value was also used for updating to the next minute to repeat the process.

The allowable input or metering rate to the subsystem is:

$$I = S_m - S^*$$ where S^* = the current storage estimate as developed above

The allowable input is constrained by the maximum and minimum metering rates at the ramp. When the allowable input is less than the minimum rate, the difference or deficiency is imposed on the adjacent upstream subsystem. Flow charts detailing the ramp metering strategy are included in a complete computer operations appendix in another project report (28).

APPENDIX B

COMPUTER OPERATING PROCEDURES

APPENDIX B

COMPUTER OPERATING PROCEDURES

This appendix deals with common operating functions concerned with the system computer (IBM 1800) utilized on the Lodge Freeway Control project. The appendix deals in turn with four separate topics: (1) Procedure for recording typewriter log information; (2) Computer malfunction check list; (3) Computer startup and coldstart; and (4) Computer shutdown. Each of these four sections describe in detail steps to be taken for each task's proper accomplishment. The instructions will be familiar to those acquainted with an IBM 1800 system.

I. Procedure for Recording Typewriter Log Information

A. On the quarter hour information pertaining to the condition of the equipment and the current state of the metering system is typed on the 1816 typewriter.

B. Malfunction messages are typed at various times when there is an unusual occurrence in the course of the metering process.

C. All information is to be written down, according to the codes given in Table B-1, on a logging form (Figure B-1) in the following manner.

1. Record <u>every</u> typed message on the log sheet.
2. Record any action taken in response to the typed message.
3. Initial every message recorded on the log sheet.
4. Record the time if it is not typed in the message or if it is different from the typed time.

D. All error messages are to be handled as described in II of this outline.

TABLE B-1

COMPUTER LOG MESSAGE CODE

Messages	Code
Detectors Down	DD (Detector numbers)
Detectors Up	DU (Detector numbers)
Northend Metering Turned On	NEMON (Time)
Data to Disk Suspended	DS (Time)
Data to Disk Restarted	DR (Time)
Overlap Begun	OB (Time)
Day Number Incremented To	DAY TO
Error	ER
Rotary Switch Change	RSC
High Min Rates	HMIN
Low Min Rates	LMIN

DAY # 0318

COMPUTER LOG

TIME	MESSAGE	ACTION TAKEN	OBSERVER
1301	OB		MP
1315	DD (20)(46)		MP
1330	No DD		LJH
1345	NDD		LJH
1400	NDD		LJH
1415	NDD		LJH
1430	DD 46 (70 min)		LJH
1445	DD 46 (85 min)		LJH
1500	DD 46 (100 min).		LJH
1515	DD 46 (~~130~~ 115 min)		MP.
1530	DD 46 (130 min)		MP.
1539	NEMON (1539)		MP.
1545	DD 46 (145 min)		MP.
1600	DD 46 (160 min)		MP.
1615	DD 46 (175 min)		MP.
1630	D.D. (46) [190] min.		MP.
1645	DD 46 (205 min)		MP.
1700	DD 46 (220 min)		MP.
1715	DD 46 (235 ")		MP.

FIGURE B-1

COMPUTER LOG SHEET

II. Computer Malfunction Check List

A. To check for malfunctions of the ramp metering system, the following procedures are to be followed.

1. Check fifteen-minute printout for proper messages as follows

    a. DETECTORS DOWN at XXXX which identifies the time when the detector stopped counting vehicles

        1) OUT (XX) which shows which detector is down

        2) XXXX MINUTES which states how long the detector has been down

    b. DETECTORS UP at XXXX identifies the time when the detectors resumed counting vehicles

        1) OUT (XX) states which detector has resumed proper operation. If this "up" message does not appear, follow Step I under II Bl.

2. Check ramps periodically for prolonged stoppages because of a constant red condition.

    a. Pan camera at the affected ramp to see if a car is present.

    b. Check typewriter printout to see if the detector is functioning properly.

        1) If detector is malfunctioning, go to STEP 1 (above).

2) If the detector is operating correctly but a car is stopped too far back for its presence to be noted by the detector, push the black button on the display panel for the appropriate detector. This changes the signal to green without recording the car in the computer count an additional time.

3. If high-pitched wail of alarm siren in Display Panel sounds, push down OP MON switch and follow Step I given under II B 1.

4. Listen for and immediately check any typing on 1816 typewriter

   a. If the message MULT EAC appears, follow Step II

B. Procedures to follow if malfunctions occur.

1. Step I.

   a. Put sense switches 6 and 7 down (off) and push the Console Interupt button on the Computer Console.

   b. A message giving the time (TIME=XXXX) should appear on the 1816 typewriter.

      1) If message appears, functioning should be normal.

2) If message does not appear, follow Step II given under II B 2.

3) Check red and green display lights on Display Panel to see if metering is cycling. If it is not, follow Step II given under II B 2.

2. <u>Step II</u>.

a. Push OP MON switch down (off).

b. Turn metering mode switches to OFF.

c. Press "STOP" on the Computer Console.

d. Press "IMMEDIATE STOP" on the Computer and then press "START" on the Console.

e. The message RELOAD should appear.

1) If this message appears, follow Step I above (II B 1).

2) If this message does not appear, go to Step 7 in the Computer Startup section which follows.

3) If the above steps fail and the malfunction continues, go to Step 7 in the Computer Startup sections.

III. Computer Startup and Coldstart

A. To be done before 1400, i.e., 2:00 p.m. or just prior to initiation of ramp metering.

B. If system is already on, go to III E.

C. Press the "POWER ON" button on the Computer Console.

D. Press and hold for approximately two seconds the "NPRO" button on the 1442 Card Reader.

E. If the 1443 Printer is ready (white light lit), go to III F.

  1. Press the "START" button on the 1443 Printer.

F. Check 1810 Disk drives for Middle drive (PROCESS PACK #04650) and Bottom drive (LET/FLET #04649).

  1. If packs are on the machine, go to III G.

  2. If packs are not on the machine, install them in the 1810.

    a. Check if the "CARTRIDGE UNLOCK" lights are lit.

      1) If not, press "STOP" and wait for this indication. (Note: if both drives are being changed, press both "STOP" buttons and wait for both cartridges to unlock.)

    b. Pull down the blue handle and remove the pack currently on the drive.

c. Put the correct pack onto the drive and lift up the blue handle.

d. Press both "START" buttons.

e. Wait for the "READY" lights to appear. (Approximately 90 seconds)

G. When both "READY" lights on the Disk are lit, go to III H.

1. If lights do not appear, repeat III F 2. d. above.

H. Clear the core at the Computer Console.

1. Press "STOP"
2. Press "IMMEDIATE STOP"
3. Put mode selector switch in "RUN"
4. Put all switches (data, sense, etc.) down except "WRITE STOR PROT BITS" switch which should be up (yes).
5. Press and hold "CLEAR STOR" button first and simultaneously press "START" button.

   a. Release both buttons.

6. Press "IMMEDIATE STOP" button.

I. Place cards in the 1442 Reader in the order given.

1. COLDSTART 1/4
2. COLDSTART 2/4
3. *CLDST <u>RSTAR</u> 1 01 3/4

4. A blank card

5. The card weight

J. Press "START" on the 1442.

1. If "READY" light appears, proceed to III K.

2. If the "READY" light does not appear

a. Lift all cards out of the reader.

b. Press and hold for approximately two seconds the "NPRO" button.

1) If any cards are stacked, remove these return to III I above.

K. Press "PROGRAM LOAD" on the Computer Console.

1. The message TURN OFF WRITE STORAGE PROTECT SWITCH will be printed on the 1816 typewriter.

L. Turn the "WRITE STOR PROT BITS" switch to off

1. Press "START" on the Computer Console.

M. The messages SSO OFF TO ZERO DATA FILE, ON TO SAVE DATA FILE ENTER DAY NUMBER -- FORMAT (I4) are printed on the 1816 typewriter.

N. The position of sense switch zero (SSO) at this point is important.

1. If this is an initial startup set sense switch zero OFF.

a. This will zero the data file.

2. If this is a restart during metering set sense switch zero ON.

    a. This will retain data already collected.

O. Type in a four digit number representing the date, i.e., February 15, 1969 becomes 0215

   1. Depress the EOF key.

P. If SSO was off at this point, a two-minute delay follows and the message "DATA FILE HAS BEEN ZEROED" appears

   1. If SSO was on the message ENTER TIME OF DAY appears.

      a. Type in a four-digit number representing the military time of the next even minute.

      b. Wait for the even minute to occur and then press the EOF key.

         1) The messages ROTARY SWITCH CHANGE 55555555 TIME = XXXX HIGH MIN RATES will be printed.

Q. If the message DATA TO DISK RESTARTED....does <u>not</u> appear, turn off sense switch 0 and wait for the message (approximately one minute).

   1. If the time is after 1301 set sense switch zero to ON and go to III R.

   2. If the time is before 1301, set SSO to OFF.

a. At 1301 the message DATA TO DISK OVERLAP BEGIN SENSE SWITCH ZERO ON TO PREVENT NEXT OVERLAP will appear.

1) Set SSO to ON.

R. Set the "OPERATIONS MONITOR" switches on the Computer Console and Display Panel to ON.

S. Set the metering switch and back up control switch on the Display Panel to "OPERATE."

T. Rotate the mode selections switches on the Display Panel to the desired settings.

1. Switch the Information Signs to "OPERATE"

2. Depress the "STATUS TRANSFER" switch.

a. If this is a restart during metering, allow signals to remain green for approximately fifteen seconds before pressing "STATUS TRANSFER."

3. The message ROTARY SWITCH CHANGE....TIME = XXXX is printed on the 1816 typewriter.

IV. Computer Shut-Down

A. Turn all rotary switches on the Display Panel controlling ramp metering modes to the "OFF" position.

1. Press "STATUS TRANSFER"

B. On the Computer Console (1801), push, in order, "STOP" and "IMMEDIATE STOP"

   1. Damage may result to the Disks if "IMMEDIATE STOP" is pushed first.

C. Push both "STOP" buttons on DISK unit (1810).

D. Push "NPRO" on the Card Reader (1442) to make sure there are no cards in the reader.

   1. If cards are in reader, they will be damaged upon powering down.

E. Push the "STOP" button on the Printer (1443).

F. Wait for the "CARTRIDGE UNLOCKED" lights for both drives to appear on Disk Drive Unit (1810).

   1. When BOTH lights are on, push "POWER OFF" on the Computer Console.

G. Turn off "OPERATIONS MONITOR" control switch on Display Panel.

H. Turn the Information Sign Switch on the Display Panel to OFF.

I. Turn the back-up system switch to OFF (Middle position).

APPENDIX C

PROJECT STATEMENT

APPENDIX C

"Excerpts From"

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Highway Research Board
National Academy of Sciences-National Research Council

FY '67

Project Statement

Research Project Title:

Optimizing Freeway Corridor Operations Through Traffic Surveillance, Communication, and Control

General Problem Area:

Special Projects

Research Problem Statement:

To meet present and future traffic demands, the combined freeway and surface street system must operate more efficiently. Freeways through heavily developed areas have limited right-of-way which prevents, on an economic basis, their reconstruction for increased capacity. Practical measures for increasing operational efficiency of these facilities through heavily traveled corridors should be developed by judicious application of traffic surveillance, communication, and control.

Urban freeways comprise a major portion of the traffic-carrying capacity of the total vehicular route system in American cities. It is believed that surveillance, communication, and control of traffic on freeways as well as on the supplemental street systems can be improved, resulting in better service to the motoring public as a whole.

It is desired to apply the best traffic surveillance, communication, and control techniques in a typical urban freeway corridor and to study the results. Innovations that may be expected to enhance the operational efficiency should be explored.

The National Proving Ground for Freeway Surveillance Control and Electronic Traffic Aids located on the John C. Lodge Freeway in Detroit has been extensively equipped for freeway surveillance, and this freeway and the adjacent corridor is designated as the study site to develop and evaluate improved surveillance, communication, and control techniques.

Objectives:

1. Determine method(s) for increasing the effectiveness of the system which involves the freeway and the adjacent surface street network within the corridor. Evaluate the methods on the study site with or without the use of additional hardware.

2. Recommend equipment configurations (that is, type and location) for the improved system which will represent the optimum balance in cost-effectiveness.