Effects of Partial Lighting on Traffic Operations at a Freeway Interchange

MICHAEL S. JANOFF AND MARK FREEDMAN

The objective of this paper is to report the results of an experiment that evaluated the effects of partial interchange lighting, complete interchange lighting, and no lighting on traffic operations at a freeway interchange. A freeway interchange that possessed a modern and complete lighting system was chosen for the experiment. The lighting was temporarily modified so that two levels of partial lighting and unlit conditions could be provided. Traffic operational data that consisted of velocities, accelerations, brake occurrences, gore and shoulder encroachments, high-beam use, and diverging and merging patterns were collected for five study conditions—daylight, complete lighting, partial lighting (two types), and no lighting—for both an exit and an entrance ramp by using a newly designed data-collection system capable of recording complete trajectory information on individual vehicles. The results indicated that complete interchange lighting is superior to partial interchange lighting in providing smoother and safer nighttime operations at the interchange.

As a means of facilitating the driving task and reducing the potential for accidents, partial lighting of interchanges has been used for areas where complete or continuous lighting was not deemed to be justified. The use of partial lighting is based on the premise that it will provide many of the benefits attributable to complete interchange lighting at lower costs. This premise has never been substantiated, and there are many who question the effectiveness of partial lighting. There has been a long-standing need for information that could form a basis for guidance concerning the effectiveness and conditions that favor the use of partial lighting of interchanges.

RESEARCH OBJECTIVE

The objective of this research, which was sponsored by the National Cooperative Highway Research Program (NCHRP), is to determine the effectiveness of partial lighting of interchanges in comparison with complete interchange lighting and no lighting and to develop recommendations for its use. For purposes of this research, partial lighting is defined as lighting that consists of a few luminaires located in the general areas where entrance and exit ramps connect with the through traffic lanes of the freeway.

To accomplish part of this objective, an interchange with appropriate geometric design, traffic flow, and a modern complete interchange lighting (CIL) system was identified. Permission was obtained from the highway lighting authority to temporarily modify the lighting system so that both partial interchange lighting (PIL) and no-lighting conditions could be provided during any chosen night at the interchange. In this manner, all other variables (geometry, traffic, environment, etc.) remained fixed so that the effect of the different lighting conditions on traffic operations could be assessed.

This paper is a report on the results of an experiment that evaluated the traffic safety and operational effects of PIL, CIL, and no lighting on traffic operations at a freeway interchange located near Philadelphia.

The remainder of this paper is organized into five parts: (a) experimental design, which included site selection, definition of independent variables and selection of dependent measures; (b) design and development of the data-collection system; (c) installation of equipment and data collection; (d) data analysis; and (e) results and conclusion.

EXPERIMENTAL DESIGN

Site Selection

A freeway interchange was required that possessed the following characteristics:

1. Modern CIL lighting system that could be physically modified to produce a variety of configurations of PIL and no-light conditions;
2. Cooperative authorities who would allow us to temporarily change the lighting from CIL to PIL and no lighting;
3. Modern geometric design with good markings, signing, surfaces, and shoulders and no severe grades or curves;
4. Suburban environment;
5. Sufficiently high night traffic volumes to allow for a high data-collection rate (200 vehicles/night); and
6. Close proximity to our offices.

A site was selected on the Pennsylvania Turnpike (PATPK) at the junction of I-276 (east-west route) with PA-9 (the turnpike's northeast extension). (This is not a tolled exit but a true interchange.) The interchange is a three-leg design that satisfies all of the criteria and was only 5 miles from our offices. Figure 1 illustrates the site. The lighting consists of 250-W high-pressure sodium (HPS) luminaires at a 30-ft mounting height and spaced about 180 ft apart.

Selection of Independent Variables

PIL Configurations

Based on the results of a nationwide survey of interchange lighting practices (1), two PIL configurations were selected. These included two lights per ramp, called PIL-2 (the California system), and four lights per ramp, called PIL-4 [the American Association of State Highway and Transportation Officials (AASHTO) system]. The location of these luminaires was derived from the same survey. They are illustrated in Figure 2 for the exit ramp. (The exit ramp is used for illustrative purposes; the entrance ramp configurations are almost identical.)

Independent Variables

The primary independent variable was the lighting configuration (day, CIL, PIL-4, PIL-2, and no light), and this was quantified by the following photometric measures: number of luminaires (and total flux) and average illuminance and uniformity. In the future, we will also determine glare (disability), pavement luminance (average), and visibility index.

Selection of Dependent Measures

The dependent measures selected for analysis cover a wide spectrum and include the following:

Figure 1. Pilot site (I-276/PA-9).

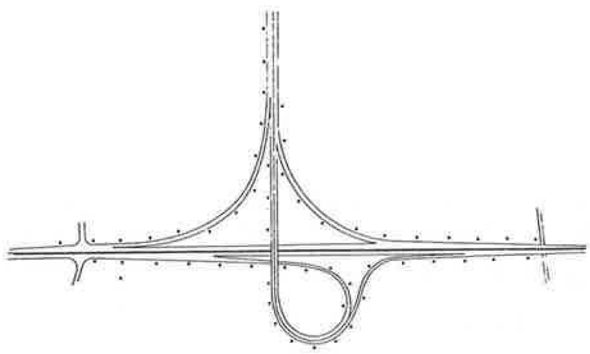
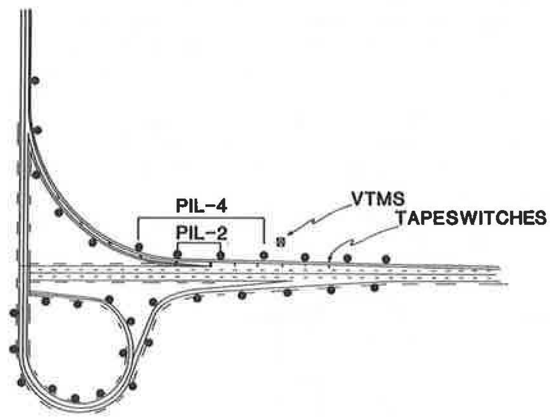


Figure 2. Exit ramp.



1. Velocity, acceleration, and acceleration noise in the deceleration and acceleration lanes and in the ramps themselves;
2. Diverge and merge distributions of drivers who use the exit and entrance ramp, respectively; and
3. Erratic maneuvers such as frequencies of braking, use of high beams, and gore and shoulder encroachments.

These measures can be stratified into two categories: those related to the beacon effect of interchange lighting (i.e., the lighting serves to identify where the interchange is) and those related to the driver-control effect of interchange lighting. The first type includes the diverge and merge point and velocity and acceleration in these areas, while the second type includes velocity and acceleration in the ramps and erratic maneuvers.

It was hypothesized that, as the lighting conditions were modified (CIL to PIL to no lighting), and since no other variables were changed, any measurable differences in the dependent measures would result from the change in lighting.

DESIGN AND DEVELOPMENT OF DATA-COLLECTION SYSTEM

The data-collection system designed and fabricated for this study--the vehicle trajectory measurement system (VTMS)--is a simplified version of the Federal Highway Administration (FHWA) traffic evaluator system (TES). VTMS has the capability of recording the time-position history of an individual lead vehicle traversing an instrumented section of roadway--in this case, the exit or entrance ramp. (TES has the capability of simultaneously recording the time-position history of all vehicles in a section of multilane roadway.) Because our experimental plan required the analysis of only individual lead vehicles (the behavior of following drivers is influenced more by the lead driver than by lighting), the VTMS was sufficient for our study.

VTMS consists of four parts: electronic logic and control circuit, high-speed printer, power supply, and roadway sensors that consist of tapeswitches and connecting cable. Seventeen switches were employed at each ramp: five single switches at 100-ft spacing in the acceleration and deceleration ramps and six pairs at 150-ft spacing in the ramps, beginning at the tip of the painted gore. The total length of roadway covered by the system was 1250 ft (Figure 2).

INSTALLATION AND USE OF VTMS

Determination of Instrument Placement

After visiting the site and observing traffic operations at both ramps, the tapeswitch configuration illustrated in Figure 2 was selected. The exact locations of these switches were dictated by both the type of measure (e.g., velocity and acceleration versus location), the availability (and cost) of connecting cable and tapeswitches, and past experience with data-collection systems of this type.

Installation of Equipment

Beginning about midnight on the day before data collection began, three Ketron personnel met with PATPK personnel who provided a heavy truck with a trailer-mounted flashing-arrow board, a pickup truck with an on-board flashing-arrow board, and three persons--two drivers and a flagman--to divert traffic. The tapeswitches were affixed to the roadway surface, in sequence, moving from upstream to downstream and covered with heavy duct tape. Traffic was either stopped temporarily (e.g., switches in the ramp) or diverted around the area (switches upstream of the ramp for the exit and downstream for the entrance).

Cabling was then placed along the shoulder, connections were made, and the system was tested. The entire procedure took about 4-5 h: 2-3 h for installation and the remainder for cabling and connections.

Data Collection

Data were collected by using a team of two observers. One observer, stationed upstream of the instrumented length of highway, announced to the other observer the arrival of each lead car vehicle. The second observer controlled and monitored the output of VTMS and also manually input data concerning erratic maneuvers onto the output of VTMS by pressing the appropriate push buttons on the manual input extension of the VTMS. The two observers communicated by citizen-band (CB) radio.

For the exit ramp (Figure 2), the upstream observer identified the lead car as it entered the deceleration lane. If no other lead car was being tracked by the system (i.e., within 1250 ft downstream), the vehicle's trajectory was tracked automatically. High-beam use and brake activations were spotted by either observer and recorded on the printer output by the downstream observer. The upstream observer kept a total count of all high-beam and brake use of all lead cars (whether tracked by VTMS or not).

Data collection continued for at least one entire night or for two nights if 200 vehicles were not ob-

Table 1. Study conditions.

	Sample Size		Day of Week	
Condition	VTMS	Manual	VTMS	Manual
Exit				
Day	204	216	Wednesday	Wednesday
CIL	147	189	Sunday	Sunday
PIL-2	153	212	Friday	Friday
PIL-4	269	321	Thursday/Saturday	Thursday/Saturday
No light	189	207	Wednesday	Wednesday
Entrance				
Day	176	732	Thursday	Wednesday
CIL	152	388	Monday	Wednesday
PIL-2	193	291	Saturday	Saturday
PIL-4	197	427	Friday	Friday
No light	176	334	Wednesday	Wednesday

served during the first night. For the exit, only the PIL-2 condition required two nights, and this resulted from a rain period during the first night. The PIL-4 condition for the exit was terminated after 212 data points were recorded by 11:00 p.m. because of a temporary system problem, and this is the only case with less than a full night's data.

Table 1 gives the 10 study conditions, the sample sizes, the number of nights, and the day of the week for each condition.

For the entrance ramp, location of the upstream observer proved to be problematic. During the first two lighting conditions (day and no lights), we noticed an exceedingly small percentage of brakers in VTMS data. This did not agree with observations made on three different nights by senior members of the research team. We repositioned the upstream observer and, after some trial and error concerning the exact position, finally determined an optimum placement. For this ramp, the manual observation (counts) of erratic maneuvers was normally performed on different nights than the nights on which the trajectory measurements were made. This was accomplished by recording total lead car volume and the number of lead cars that made erratic maneuvers.

Traffic volume counts on the main road and the ramps were initially desired, but malfunctions in the counters produced error-prone data, so the volumes were discarded. All nighttime study conditions had very similar traffic volumes and did not differ on different days by more than 10-15 percent at any given hour of the night. Daytime volumes were much heavier.

Data collection began on September 23, 1981, after deployment of VTMS on September 22. It continued through October 28. Rain caused complete washouts on four different nights (requiring redeployment of most of the switches) and halted data collection on three other nights. A major system failure, caused by nearby lighting, occurred on the second night of data collection for the entrance ramp and caused a two-week delay to obtain the necessary parts.

DATA ANALYSIS

The data analysis was divided into two parts: (a) manual analysis of high-beam use and brake-light occurrences and (b) computerized analysis of gore and shoulder encroachments, velocity, acceleration and acceleration noise, and the distribution of diverging patterns (for the exit) and merging patterns (for the entrance).

Manual Analysis

High-Beam Use

The table below gives the frequency of high-beam use by study condition for both the exit and entrance:

Study Condition	Frequency (%) Exit	Frequency (%) Entrance
Day	0	0
CIL	0	1.8
PIL-4	2.4	8.9
PIL-2	4.2	5.4
No light	5.8	12.6

As expected, the frequencies increased as the illumination decreased from day to CIL to PIL to no light. The greater use of high beams under PIL conditions is indicative of a lack of visibility (i.e., drivers activate their high beams to increase their seeing distance).

Brakers

The data on brakers were derived in two ways. For the exit, only VTMS-recorded lead cars were classified as either brakers or nonbrakers. For the entrance (because of observer placement problems described previously), all lead cars were classified as either brakers or nonbrakers (on nights other than those when VTMS was used). The type of data collected at the exit is a subset of the type collected at the entrance (it consisted of 75 percent of the early night volume and up to 95-100 percent of the late night volume).

The table below gives the braker data for both the entrance and exit:

Study Condition	Frequency (%) Exit	Frequency (%) Entrance
Day	40.1	74.0
CIL	45.0	73.2
PIL-4	49.1	85.9
PIL-2	48.5	84.8
No light	52.2	86.8

Again, as the lighting decreased, the percentage of brakers increased.

The higher frequencies of brake-light occurrences under the two PIL conditions are again indicative of a lack of visibility and an uncertainty associated with the task required to negotiate the interchange ramps.

The braker data were further classified by time period--early (8:00-11:00 p.m.) and late (1:00-5:00 a.m.)--which corresponded to higher and lower (than average) volumes. It was disclosed that the frequency of brakers normally increased during higher volumes and decreased during lower volumes (for the four night conditions).

Other Manual Analysis

We attempted to observe and record gore and shoulder encroachments manually, but this proved to be impossible under the PIL and no-light conditions because the gore markings could not be seen by the observers under these low-light conditions. These data were instead analyzed from VTMS data.

Computer Analysis

The vehicle trajectory data (time in milliseconds at which the front wheels of each vehicle encountered each switch) were manually transcribed onto coded data-reduction forms and then keyed to a disk file. Preliminary data screening was accomplished during the transcription process to remove those data records with gross errors.

The computer program was designed to perform four different operations: error checks, individual record calculations (for each vehicle), pooled data calculations (for each location of each study condition), and summary statistics (for each study condition), as follows.

Error Checks and Reconstruction

1. Data screening for miscodings or logical errors and reasonableness tests to identify times that are excessively out of range (e.g., a time of 5 s between two switches when the average time between preceeding switches is only 1 s), and
2. Reconstruction of time profiles when one or more switches were temporarily out of operation.

Individual Record Calculations

1. Compute spot speed across each pair of switches and average speed between consecutive individual switches or pairs for each record,
2. Compute spot acceleration from consecutive spot speed and average accelerations from consecutive average speeds for each record,
3. Compute average acceleration noise from consecutive average accelerations, and
4. Compute individual diverge or merge points for each vehicle that traverses the exit or entrance ramp and identify unusual or dangerous exit points from the system--both exit and entrance (i.e., a record in which the first switch hit was located downstream of the beginning of the gore on the exit ramp, or before the point of the gore on entrance ramp; these are equivalent to gore and shoulder encroachments).

Pooled Data Calculations

1. Compute means of spot speed and frequencies of switch hits across each pair of switches and compute means of average speed and frequencies between consecutive switches or pairs for each study condition,
2. Compute means of spot acceleration and frequencies between consecutive pairs of switches and compute means of average acceleration across three consecutive pairs or individual switches for each study condition,
3. Compute means of average acceleration noise across four consecutive switches or pairs for each study condition,
4. Compute mean diverge (merge) speed and frequencies at each diverge (merge) point for all study conditions for exit (entrance) ramp, and
5. Compute frequencies and locations of unusual exit points for all study conditions.

Summary Statistics

The following summary statistics were given for each study condition: number of records, accepted records, and errors (rejected data), and number of cars and trucks.

RESULTS

Eight sets of data were output by the computer program for each study condition:

1. Average velocity by location by study condition,
2. Average acceleration by location by study condition,
3. Average acceleration noise by location by study condition,
4. Spot velocity by location by study condition,
5. Spot acceleration by location by study condition,
6. Average diverge velocity (exit) and merge velocity (entrance) by location by study condition,
7. Distribution of diverging patterns (for exit) and merging patterns (for entrance), and
8. Frequencies of unusual (dangerous) exiting vehicles from VTMS (equivalent to gore and shoulder encroachments).

Velocity, Acceleration, and Acceleration Noise

It was hypothesized that, as the lighting conditions changed, a systematic measurable change in these variables would be noticed. This proved to be false. All three of these variables, whether computed as an average value between switch locations or as spot value at switch pairs, proved to be insensitive to the changes in the independent variable. Although certain differences were found (e.g., day velocities higher than night velocities; night no-light velocities greater than all night-lighted velocities), these differences were quite small (e.g., 1-3 ft/s) and did not distinguish between CIL and PIL conditions.

Diverge and Merge Patterns

The table below summarizes the diverging and merging patterns for the exit and entrance:

	Frequency (%)	
Study Condition	Exit (diverging late)	Entrance (merging early)
Day	51.0	37.5
CIL	20.0	36.2
PIL-4	25.5	47.7
PIL-2	26.1	47.2
No light	26.9	26.1

It is evident from the data that, at the exit, drivers diverge farther downstream under PIL conditions than under the CIL condition, and at the entrance they merge earlier under the PIL conditions than under the CIL condition.

This later divergence at the exit is probably indicative of more uncertainty concerning where the exact location of the ramp is, while the earlier merging at the entrance is probably indicative of the uncertainty concerning where the end of the acceleration ramp is.

Unusual Exiters

Drivers who left the VTMS after the gore (for the exit) or before the gore (for the entrance) either (a) crossed the gore into the main stream of traffic or (b) encroached on the left shoulder. Either condition would be indicated by a VTMS output that stopped after the last contacted switch.

An example of a gore encroachment for the exit would consist of a vehicle passing over switches 1 through 7, then not passing over switches 8 through 17. A typical shoulder encroachment would consist of a driver passing over switches 1 through 11 and missing switches 12 through 17. For the entrance, a shoulder encroachment would consist of a driver passing over switches 1 through 4, 1 through 6, or 1 through 8, and missing the rest, while a gore encroachment would consist of passing over switches 1 through 10 and missing the rest.

The table below summarizes the frequencies of unusual exiters for both the exit and entrance ramp:

	Frequency (%)	
Study Condition	Exit	Entrance
Day	3.9	1.7
CIL	4.8	1.3
PIL-4	8.5	10.4
PIL-2	6.0	9.6
No light	4.3	2.8

Table 2. Summary of results.

Measure	Result: Exit	Result: Entrance	Interpretation
Frequency of high-beam use	Increases with each decrease in lighting: CIL to PIL-4 to PIL-2 to no lighting	Increases as lighting decreases: CIL to PIL to no lighting (reversal in PIL cases)[a]	CIL better than PIL
Frequency of brakers	Increases as lighting decreases: day to CIL to PIL to no lighting (PIL cases the same)	Increases as lighting decreases: day to CIL to PIL to no lighting (reversal in PIL cases)[a]	CIL better than PIL
Frequency of unusual exiters[b]	Increases as lighting decreases: day to CIL to PIL to no lighting (reversal in PIL cases)[a]	Increases as lighting decreases: CIL to PIL to no lighting (reversal in PIL cases)[a]	CIL better than PIL
Diverge and merge patterns	Drivers diverge later under PIL than under CIL	Drivers merge earlier under PIL than under CIL	CIL better than PIL

[a]PIL-2 better than PIL-4.
[b]For gore and shoulder encroachments.

Again, the frequencies under the PIL conditions are higher than under the CIL condition.

Both of these maneuvers are indicative of erratic or dangerous behavior and probably result from either lack of control caused by inadequate visibility or uncertainty.

INTERPRETATION OF RESULTS AND STATISTICAL ANALYSIS

Table 2 summarizes the results for the four maneuvers (high beams, brakes, unusual exiters, and diverge and merge patterns) and provides an interpretation of each result.

For each of the four variables, CIL is better than PIL for both the exit and entrance ramp and, in one-half of the eight study conditions (three of four for entrance; one of four for exit), PIL-2 is better than PIL-4.

Statistical analyses (t-tests) revealed that, except for the occurrence of brakers at the exit, CIL performs significantly better than PIL. Further, although the difference between CIL and PIL was not significant for the breakers at the exit, the trend in this case clearly indicates the same pattern. In addition, there is a significant difference between the two PIL conditions in only three of the eight tests, which indicates little difference in performance between the two PIL conditions.

Additional statistical comparisons revealed the following:

1. Significantly better performance during daylight than at night (five of six comparisons),
2. Significantly better performance under CIL than under no light (seven of eight comparisons),
3. Better performance under PIL than under no light in only five of eight comparisons, and
4. Better performance under light than no light in only five of eight comparisons.

CONCLUSIONS

Based on the analyses performed on the four types of data described in the previous section, it appears that driver performance under CIL is significantly better than under either of the PIL conditions. The frequency of the erratic-behavior measures all increase under PIL in comparison with CIL and frequently decrease again under the no-light condition (see, for example, the tables under the headings of Unusual Exiters and Diverge and Merge Patterns). In addition, driver performance under PIL-2 is often superior to that under PIL-4 (see in Table 2 those entries that are referenced with a footnote).

It is hypothesized (but as yet unproven) that drivers are experiencing transitional visibility problems under the PIL conditions when they are forced to drive from dark to light to dark areas and at the same time perform a relatively complex maneuver: diverge or merge plus track a 90° curve. The problem is made more difficult under the PIL-4 condition when the lighted area is about 550 ft long (8 s at 70 ft/s) than under PIL-2 when the lighted area is only 180 ft long (2.5 s).

Photometric measurements were made at the exit ramp under CIL and PIL-2 conditions. Illumination, pavement luminance, object luminance, and glare luminance were all measured under both lighting conditions. Illuminance and all other luminances were roughly proportional to the number of lights under each lighting condition, as was visibility, which was calculated from the three luminances. No systematic relation was found between either of the photometric measurements and any of the driver-behavior measures.

This experiment will be repeated at a second interchange (a full cloverleaf type) by using the same measures and a slightly modified tapeswitch arrangement, which will cover a longer section of roadway.

ACKNOWLEDGMENT

This work was sponsored by AASHTO in cooperation with FHWA and was conducted in NCHRP, which is administered by the Transportation Research Board (TRB) of the National Research Council.

The opinions and conclusions expressed or implied in this paper are ours. They are not necessarily those of TRB, the National Academy of Sciences, FHWA, AASHTO, or the individual states that participate in NCHRP.

REFERENCE

1. Partial Lighting of Interchanges--Summary of North American Practices. NCHRP, Interim Rept., July 1981.

Publication of this paper sponsored by Committee on Visibility.