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Title: **Dynamic Late Merge Control Concept for Work Zones on Rural Interstate Highways**

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ABSTRACT

Conventional traffic control plans for lane closures of rural interstate normally work well as long as congestion does not develop. However, when the traffic demand exceeds the capacity of the work zone, queues may extend back passed the advance warning signs, often surprising approaching traffic and increasing the accident potential. Also, smooth and orderly merging operations may be lost as some drivers remain in the closed lane attempting to squeeze into the open lane at the head of queue while other drivers try to prevent drivers in the closed lane from passing them by straddling the centerline or traveling slowly in tandem with another vehicle in the closed lane. These maneuvers tend to reduce the capacity of the merging operation and increase the accident potential and road rage among drivers. The *Early Merge* and *Late Merge* are two forms of merge control designed to deal with these problems. However, they also have operational characteristics that limit their effectiveness under both congested and uncongested traffic flow conditions. This paper examines the advantages and disadvantages of each approach. It then describes a new concept called the *Dynamic Late Merge*, which features the integration of the *Late Merge* and the conventional lane closure merge control based on real-time measurements of traffic conditions in advance of the lane closure.

key words: work zones, single lane closures

INTRODUCTION

The single lane closure is a common application of temporary traffic control on rural interstate highways. It is used where one lane is closed to traffic to provide a work space. It is also used in advance of median crossovers where one roadway is closed to traffic to provide a work space and two-lane, two-way traffic is maintained on the other roadway. According to the typical traffic control plan used by the Nebraska Department of Roads (NDOR), drivers are advised of the lane closure by advance lane closed signs placed on both sides of the roadway at 1610 meters (1 mile) and 805 meters (½ mile) in advance of the taper. In addition, lane reduction symbol signs are placed on both sides of the roadway at 460 meters (1,500 feet) in advance of the taper and a flashing arrow panel is usually placed at the beginning of the taper. This control plan, which is referred to as the *NDOR Merge* in this paper, is shown in Figure 1.

This traffic control plan normally works well during most hours of the day when traffic demand is less than the capacity of the open lane. However, when the demand exceeds the capacity, congestion develops and problems occur. The shock wave associated with the developing congestion increases the potential for rear-end accidents, especially when the congestion extends upstream beyond the advance lane closure signs. When this happens, drivers may not be prepared to stop, because they have not passed by the advance warning signs. They also have not been informed about which lane is closed. Therefore, drivers in the closed lane are not prepared to move to the open lane and they may be enraged when blocked by slower vehicles attempting to prevent them from merging into the open lane ahead. Also, drivers, who are in the open lane, may be upset when passed by drivers in the closed lane.

A recent NDOR study *(1)* identified two basic approaches that are used to address these problems. One approach is the *Early Merge*, which is designed to encourage drivers to merge into the open lane sooner than they would with the *NDOR Merge*. The other approach is the *Late Merge*, which is designed to encourage drivers to remain in their lanes until they reach the merge point at the lane closure taper. This paper examines the advantages and disadvantages of each approach with respect to the *NDOR Merge*. The paper then describes a new concept called the *Dynamic Late Merge*, which features the integration of the *Late Merge* and the conventional mode of merge control based on real-time measurements of traffic conditions in advance of the lane closure.

EARLY MERGE

Several schemes have been used to encourage drivers to merge into the open lane farther in advance of the lane closure. These strategies are of two basic types, static and dynamic.

Static Early Merge Strategies

Static forms of the *Early Merge* provide advance notice at a fixed distance ahead of the lane closure. These strategies include the placement of additional advance lane closed signs at approximately 1610-meter (1-mile) intervals for several kilometers in advance of the lane closure. The additional signs reduce the chances of drivers encountering congestion without knowing which lane is closed. This knowledge enables them to merge into the open lane before arriving at the end of the queue and having to squeeze into the open lane between vehicles in the queue. Also, the early advance lane closure notice may reduce rear-end accident potential by alerting drivers to the possibility of congestion farther in advance of the lane closure. Simulations conducted by Nemeth and Rouphail *(2)* found that early merge control strategies significantly reduced the frequency of forced merges, especially at higher traffic volumes. On the other hand, simulations by Mousa *et al (3)* determined that early merge control strategies increased the travel times through the work zone, because vehicles are more likely to be delayed over greater distances by slower vehicles ahead of them in the open lane. This may in turn increase the likelihood of drivers in the open lane attempting to use the closed lane to pass slower vehicles, which would increase the potential of lane-change accidents. Some states *(1)* use lane drop arrows, rumble strips, and/or no-passing zones for distances of up to 1610 meters (1 mile) or more in advance of the lane closure to discourage drivers from using the closed lane to pass.

Dynamic Early Merge Strategies

Dynamic forms of the *Early Merge* provide advance notice over a variable distance ahead of the lane closure based on real-time measurements of traffic conditions. One example is the *Indiana Lane Merge* developed by the Indiana Department of Transportation, which is illustrated in Figure 2. This system creates a dynamic no-passing zone to encourage drivers to merge into the open lane before reaching the end of a queue caused by congestion, and to prohibit them from using the closed lane to pass vehicles in the queue and merge into the open lane ahead of them. The system uses sonic detectors to determine the presence of a queue in the open lane. The detectors are mounted on DO NOT PASS signs with two flashing strobes and WHEN FLASHING supplementary plates as shown in Figure 3. The signs are installed adjacent to the closed lane at 400- to 800-meter (¼- to ½-mile) intervals for up to 4 kilometers (2.5 miles) or more in advance of the lane closure. When stopped vehicles are detected in the open lane next to a sign, a signal is transmitted to turn on the flashing strobes on the next sign upstream. When vehicles are moving again, the strobes are shut off. In this way, the length of the no-passing zone is tailored to the length of congestion present.

The system was field tested during the 1997 construction season by the Indiana Department of Transportation. It was found to smooth the merging operations in advance of the lane closure.

Drivers merged when they were supposed to merge and flow in the open lane was uniform with very few rear-end accidents. However, the system did not increase throughput, and the results of a simulation study by Purdue University *(4)* indicated that travel times through the work zone are longer. The field tests also determined that the spacing of the signs should be logarithmic instead of uniform in order to account for the reduction in speed as traffic approaches the lane closure. Preliminary benefit-cost estimates by the Indiana Department of Transportation indicate that implementation of the system is justified at lane closures where the capacity of the single lane will be exceeded at least 15 to 20 times per week.

The NDOR conducted field studies *(1)* to compare the *Indiana Lane Merge* and the *NDOR Merge*. The study sites were right lane closures. Previous research *(2,3,5)* has cited the lane distribution of traffic approaching a lane closure as being indicative of the effectiveness of the merging operations. The lane distributions within 915 meters (3000 feet) of the lane closures observed in the NDOR study are shown in Figure 4. These distributions indicate that vehicles moved into the open lane sooner with the *Indiana Lane Merge* than they did with the *NDOR Merge*. Also, the merging operations with the *Indiana Lane Merge* occurred more uniformly over a much longer distance than they did with the *NDOR Merge*, which were concentrated over a 150-meter (500-foot) section approximately 360 meters (1200 feet) in advance of the lane closure. Spreading the merging over a longer distance produced smoother merging operations. Only seven forced merges were observed in 16 hours of data collection during moderate to high traffic volumes at the *Indiana Lane Merge* study site over a 4-day period in July 1998; whereas forced merges were observed at the rate of 20 or more per hour under comparable levels of traffic volume at the *NDOR Merge* study site.

LATE MERGE

The *Late Merge* is opposite of the *Early Merge* in that it is designed to encourage drivers to use either the open or closed lane until they reach the merge point at the lane closure taper rather than merging as soon as possible into the open lane. One example of the *Late Merge* is the system developed by the Pennsylvania Department of Transportation (PennDOT). This system was implemented as a means to reduce the road rage engendered between drivers who merge into the open lane early and those who remain in the closed lane and merge into the open lane near the front of the queue at the last minute. A typical traffic control plan for the PennDOT *Late Merge* is shown in Figure 5. Approximately 2.4 kilometers (1.5 miles) in advance of the lane closure, USE BOTH LANES TO MERGE POINT signs are placed on both sides of the roadway as shown in Figure 6. These signs are followed by conventional ROAD WORK AHEAD and advance lane closed signs. Finally, MERGE HERE TAKE YOUR TURN signs are placed on both sides of the roadway near the beginning of the taper as shown in Figure 7.

The primary intent of the *Late Merge* developed by the PennDOT is to reduce the road rage between early and late mergers by informing drivers that it is permissible for traffic to travel in both lanes to the merge point. Although it is not standard practice, the *Late Merge* is used regularly at work zones on interstate highways by one PennDOT district office. No problems have been reported with its use, and it seems to be well received by drivers. A study of its operational effects found that it increased the capacity of the merging operations by as much as 15 percent *(6)*.

Since the *Late Merge* seems to address many of the problems experienced with the *NDOR Merge* during congestion, the NDOR also conducted field studies *(1)* to compare the safety and operational effects of the PennDOT *Late Merge* and the *NDOR Merge*. The results of these studies revealed that the conflict rates are substantially lower with the *Late Merge*. As shown in Figure 8, at higher densities, about 75 percent fewer forced merges and 30 percent fewer lane straddles were observed for the *Late Merge*; and, at densities below 16 veh/km (25 vpm), no conflicts were observed for the *Late Merge*, whereas conflicts were observed for the *NDOR Merge*. The studies also found the capacity of the *Late Merge* to be nearly 20 percent higher than that of the *NDOR Merge*.

Conceptually the *Late Merge* addresses many of the problems that are associated with traffic operations in advance of lane closures at work zones on rural interstate highways, especially during periods of congestion. In particular, the lengths of the queues that form as a result of congestion are reduced by about 50 percent, because the queued vehicles are stored in two lanes instead of only one. The shorter queue lengths reduce the likelihood of them extending back beyond the work zone's advance warning signs and surprising approaching drivers, which in turn reduces the potential of rear-end accidents. In addition, driver experience less anxiety about knowing which lane is closed, because either lane can be used to reach the merge point. The availability of both lanes also reduces the frustration levels of drivers. Drivers in the open lane are less likely to be irritated by others passing by them in the closed lane, because this maneuver is permissible with the *Late Merge*. Drivers are able to select the lane with the shortest queue and not be concerned about others blocking their path to the merge point.

However, despite the obvious advantages of the *Late Merge* during peak traffic flow conditions, there is a concern about the safety of its operation during off-peak periods when traffic demand is below the capacity of the open lane and traffic speed is high. Under these conditions, it may be more difficult for drivers to decide who has the right-of-way. This indecision could increase the potential for collisions at the merge point. This was not found to be a problem at the *Late Merge* study site in the NDOR study *(1)*. At this location, drivers merged according to the *Early Merge* concept during off-peak periods, because, as shown in Figure 5, the USE BOTH LANES TO MERGE POINT signs were followed by a series of advance lane closed signs which enabled them to merge into the open lane before reaching the merge point. Although these signs may have improved the safety of the merging operation during the off-peak periods, they also seemed to reduce the effectiveness of the *Late Merge* during peak periods, because some drivers did not stay in the closed lane until the merge point. Instead, they slowed to merge into the open before the merge point. This behavior often resulted in some forced merges which reduced both the safety and capacity of the merging operation.

DILEMMA

The results of the NDOR study *(1)* indicate that both the *Early Merge* and *Late Merge* provide safer merging operations than the *NDOR Merge*. Both systems were observed to have lower merging conflict rates than the *NDOR Merge*. But, there is a concern about the potential for driver confusion at the merge point of the *Late Merge*, especially under high-speed, low-volume conditions, which could adversely affect safety. On the other hand, the *Late Merge* was found to have a higher capacity than the *NDOR Merge* and the *Early Merge (1)*. The *Late Merge*'s higher capacity and larger queue storage area reduce the probability of congestion extending back beyond the advance warning signs; thus, reducing the potential of rear-end collisions on the approach to the work zone. The higher capacity also reduces the duration of congestion, which in turn reduces the exposure to rear-end collisions. In addition, because of its higher capacity, the *Late Merge* reduces congestion delay; whereas, the *Early Merge* has been found to increase travel times, especially under high traffic volumes *(3,4)*.

Based on these findings, the best system of merge control during peak periods is the *Late Merge*. However, because of the safety concerns regarding its operation under high-speed, low-volume conditions, the *Late Merge* may not be the best system during off-peak periods. Therefore, in order to maintain optimum merging operations at all times, it would be necessary to convert from the *NDOR Merge* or *Early Merge* during periods of uncongested flow to the *Late Merge* during periods of congested flow. In other words, a *Dynamic Late Merge* would be needed. Forms of the *Early Merge*, which utilize pavement markings, rumble strips, or no-passing zones to discourage use of the closed lane, would not be conducive to a real-time conversion to the *Late Merge*, which uses the closed as well as the open lane. Therefore, a merge control similar to the *NDOR Merge* would be used during the uncongested periods in the *Dynamic Late Merge* system.

DYNAMIC LATE MERGE CONCEPT

The concept of the *Dynamic Late Merge* is intended to resolve the aforementioned dilemma. Its goal is to provide the safest and most efficient merging operations at all times in advance of the lane closure by switching between the *NDOR Merge*, or conventional lane closure merging operations, and the *Late Merge*, based on real-time measurements of traffic conditions. It would operate as the *NDOR Merge*, or conventional lane closure merging operations, during periods of uncongested flow, and as the *Late Merge* during congested flow conditions.

It is envisioned that the *Dynamic Late Merge* would consist of a series of advance signs that would be activated to advise drivers to "use both lanes to the merge point" when congestion is detected in the open lane adjacent to the signs in a manner similar to the *Indiana Lane Merge*. A sign would also be placed at the merge point advising drivers to "merge and take their turn doing so." When the congestion clears, the signs would be deactivated, or changed, to advise drivers of the lane closure and effect the *NDOR Merge*, or conventional lane closure merging operations. The signs could be variable message signs equipped with traffic detectors similar to the radar-equipped sign shown in Figure 9, which is used in the ADAPTIR™ developed by the Scientex Corporation in cooperation with the Maryland State Highway Administration and the Federal Highway Administration. Or, perhaps, the signs could be static signs equipped with traffic detectors and flashing strobes like the sign shown in Figure 3, which is used in the *Indiana Lane Merge*. Research is needed to determine the most effective sign message, type, and spacing. The length of signing in advance of the lane closure should be longer than the longest backup expected for the design flow rate and capacity of the work zone.

One important operations issue is the lane distribution between the open and closed lane prior to the switch from the conventional mode of merge control to the *Late Merge*. Under the conventional mode of merge control, drivers are encouraged to merge into the open lane. Therefore, when the traffic volume approaches the capacity of the conventional mode of merge control, the speed of traffic in the open lane may be much lower than the speed of traffic remaining in the closed lane. Consequently, when the system switches to the *Late Merge*, the accident potential may be high if drivers in the slower open lane attempt to merge into the higher speed closed lane before flow conditions in the two lanes are similar. Speed control and/or messages to advise drivers to stay in their lanes during the transition may be necessary to minimize this accident potential. Future research would determine the need for such measures.

CONCLUSION

Conventional traffic control plans for lane closures of rural interstate normally work well as long as congestion does not develop. But, when the traffic demand exceeds the capacity of the work zone, queues may extend back beyond the advance warning signs, often surprising approaching traffic and increasing the accident potential. Also, smooth and orderly merging operations may be lost when some drivers remain in the closed lane attempting to squeeze into the open lane at the head of queue while other drivers try to prevent drivers in the closed lane from passing them by straddling the centerline or traveling slowly in tandem with another vehicle in the closed lane. These erratic maneuvers tend to reduce the capacity of the merging operation and increase the accident potential and road rage among drivers.

The *Late Merge* addresses many of these problems, which occur during periods of congestion with the conventional mode of merge control. Previous research *(1,6)* has found that the *Late Merge* improves the safety and efficiency of merging operations, especially during congested flow conditions. However, when there is no congestion and speeds are high, potential confusion among drivers at the merge point becomes a concern. Therefore, the *Dynamic Late Merge* concept is proposed in the interest of providing the safest and most efficient merging operations at all times.

Research is needed to determine the driver information system necessary to effect the *Dynamic Late Merge* concept. Also, protocols for the transition between the conventional merge control and *Late Merge* need to be developed. These protocols would specify the traffic flow thresholds for transferring from one form of control to the other as well as the sequencing of the sign messages to effect the desired driver responses. Once a system prototype has been developed and found to perform successfully in operational tests, the roadway and traffic conditions necessary to justify the implementation of the concept should be identified. It is the authors' opinion that this research is warranted by the improvements in the safety and efficiency of traffic operations in advance of lane closures on rural interstate highways that could potentially be realized by the deployment of the *Dynamic Late Merge* concept.

ACKNOWLEDGMENT

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DISCLAIMER

The contents of this paper reflect the viewers of the authors who are solely responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the NDOR or the PennDOT. The paper does not constitute a standard, specification, or regulation.

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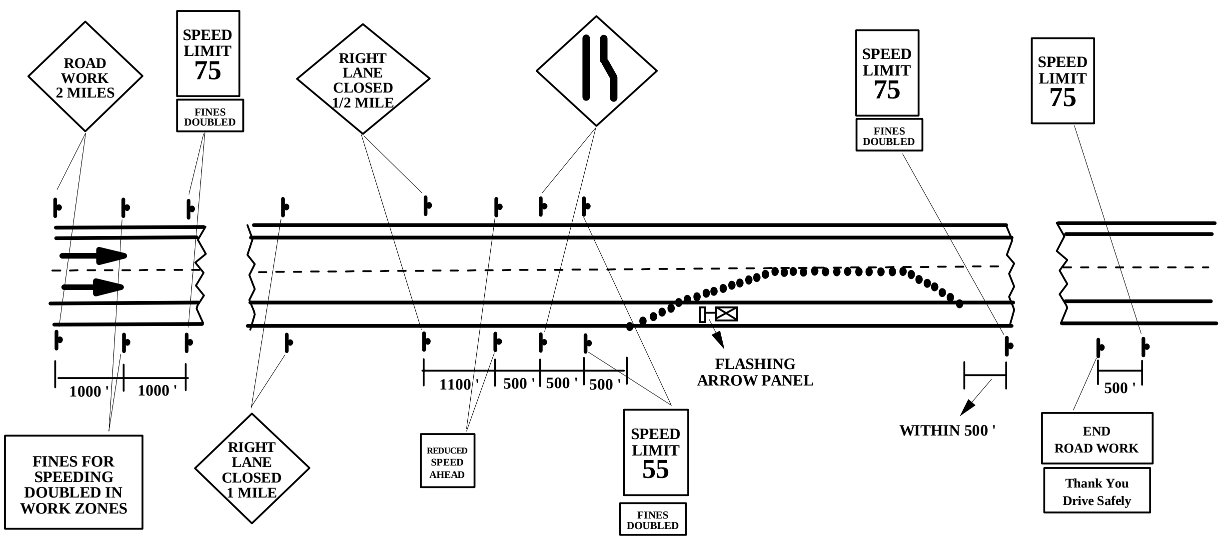

FIGURE 1 NDOR Merge.

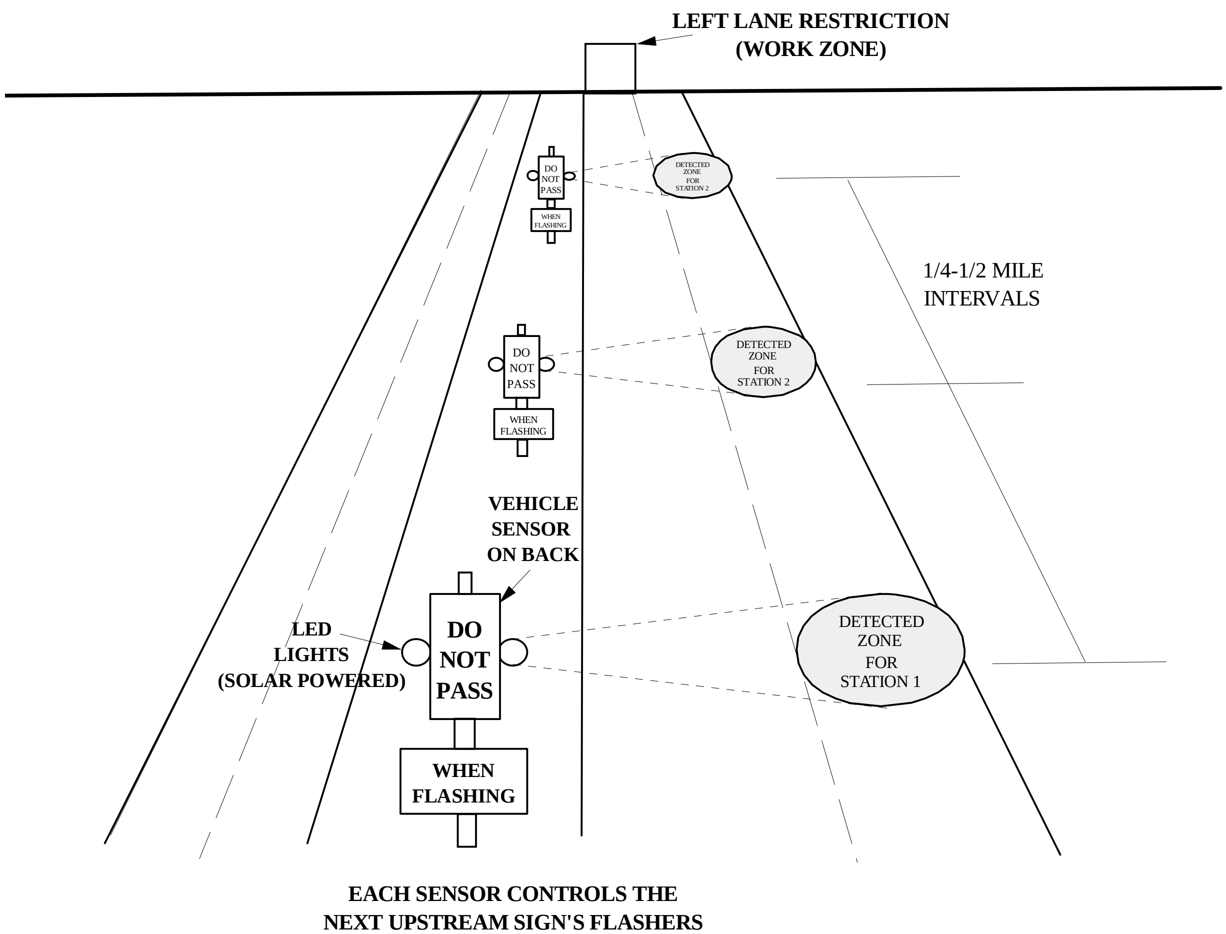

FIGURE 2 Indiana Lane Merge.

FIGURE 3 DO NOT PASS WHEN FLASHING Sign.

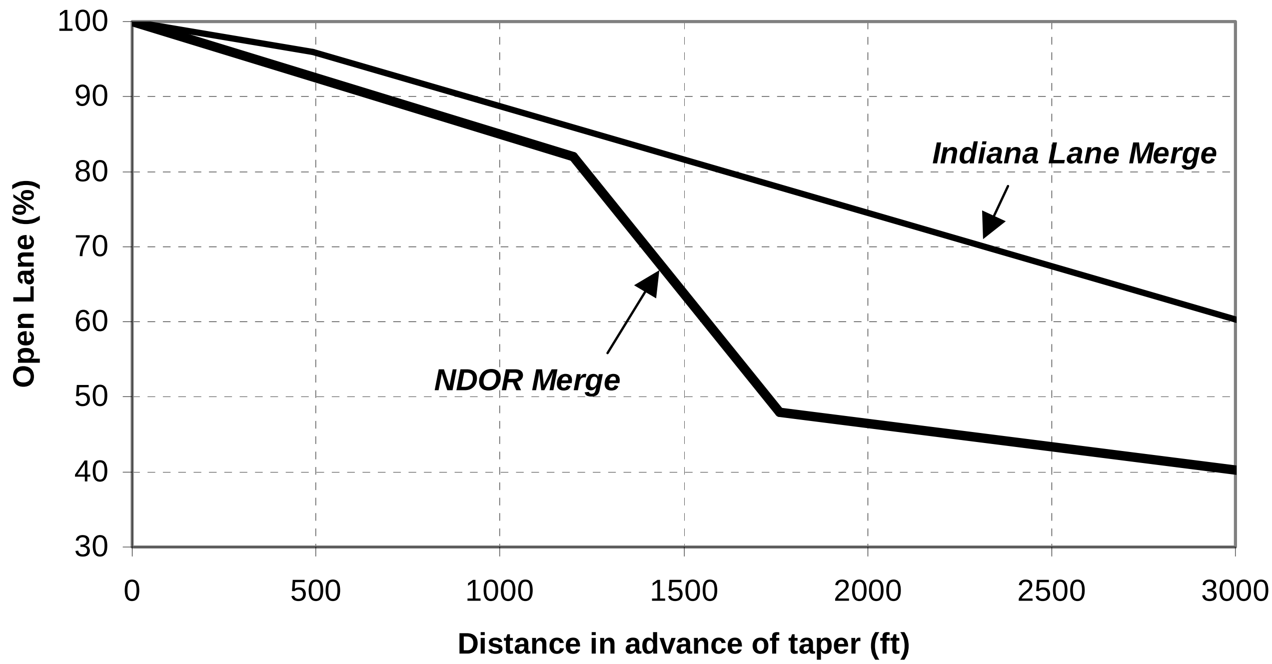

FIGURE 4 Lane Distribution.

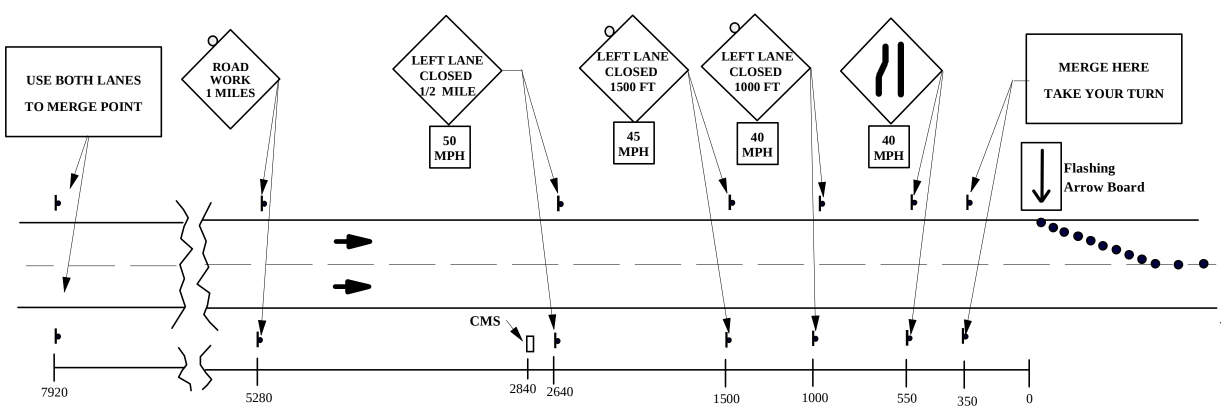

FIGURE 5 Late Merge.

FIGURE 6 USE BOTH LANES TO MERGE POINT Sign.

FIGURE 7 MERGE HERE TAKE YOUR TURN Sign.

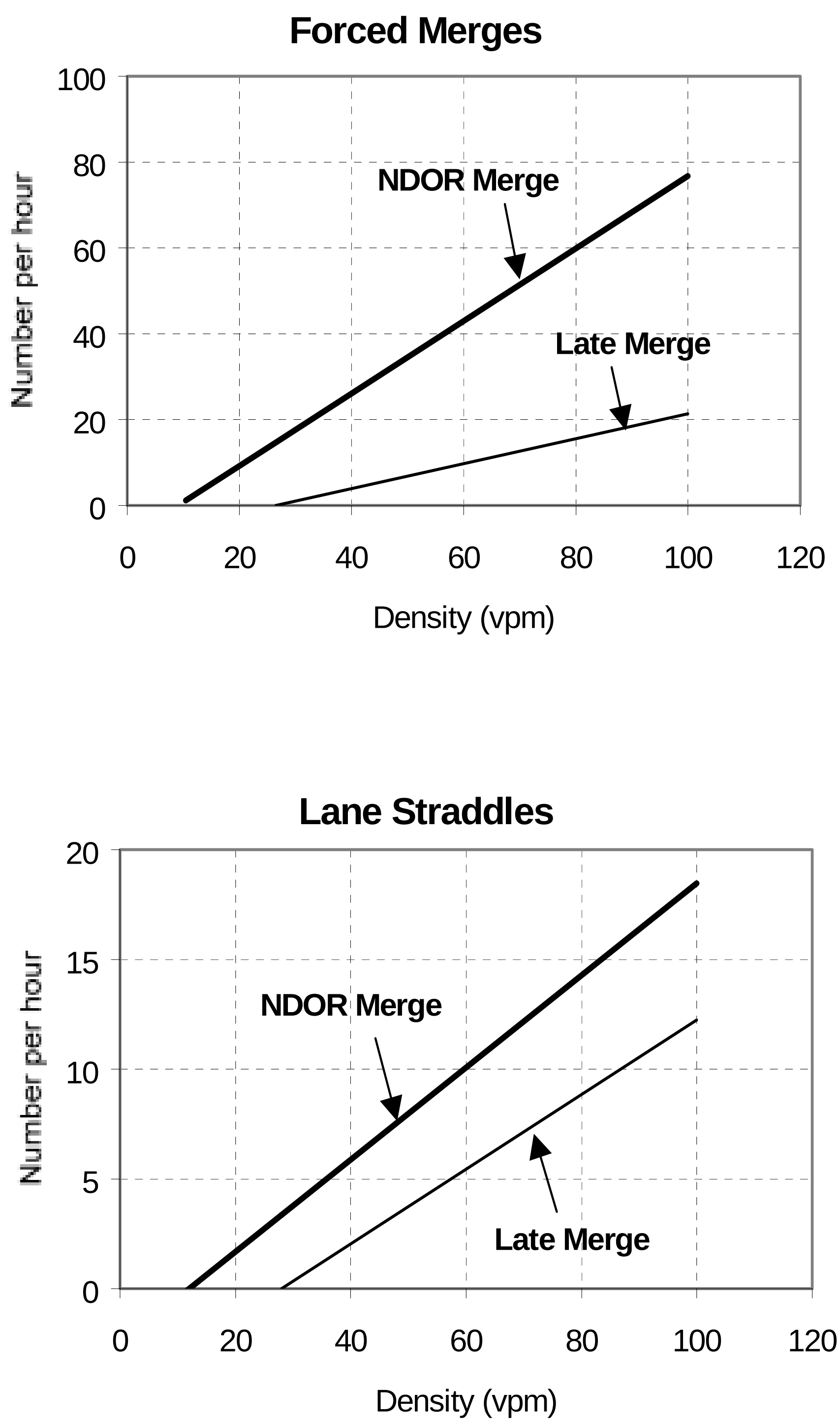

FIGURE 8 Traffic Conflicts.

FIGURE 9 ADAPTIR^{TM} Variable Message Sign.