Traffic Analysis for Highway-to-Highway Interchanges on Automated Highway Systems
Congestion in Absence of Dedicated Ramps

BIN RAN, SETH JOHNSON, SHAWN LEIGHT, AND JACOB H.-S. TSAO

Special connector ramps linking the automated lanes at automated highway–to–automated highway interchanges may be needed to enable continuous automated driving between two crossing highways. Although a typical cloverleaf configuration has only two levels and is more amenable for such additions, the sharp curvature of this design usually imposes constraints on traffic speed and flow. Because of these constraints, most highway-to-highway interchanges in urban areas have straighter lanes but tend to involve three or more levels. Building the additional connector ramps to accommodate eight high-speed turning movements at an area where the geometry is already complex could be difficult or costly. Therefore, proponents of automated highway systems (AHS) face a major dilemma. This dilemma is studied, including the impact of not providing automated connector ramps on the manual and AHS traffic on manual lanes at or near a highway-to-highway interchange. It is shown that, with a typical cloverleaf design, in the absence of the additional connector ramps, any moderate to heavy AHS-changing traffic could severely disturb the flow of through traffic, seriously exacerbate congestion, and possibly cause a traffic breakdown at the interchange area. These effects will most likely negate any mainline throughput benefits for which an AHS is designed.

The concept of automated highway systems (AHS) began in the 1960s but has received renewed attention recently because of the fast-worsening problem of urban highway congestion. In an AHS, the integration of advanced sensor, communication, and computer and control technologies may safely reduce average vehicle headways, resulting in higher throughput flows operating at higher average speeds.

In a recent comprehensive treatment of conceptual AHS design, Stevens (*1*) discussed AHS deployment and operations goals, analyzed AHS characteristics, and identified 37 alternative AHS concepts. The authors adopt his definition of an AHS as a vehicle-highway system that supports hands-off and feet-off driving on dedicated lanes. At this stage, whether the driver can be completely disengaged from the driving tasks throughout the travel on AHS, subject to safety requirements, remains an open issue. However, it is assumed in this paper that drivers are disengaged from the driving task only while on the dedicated lanes of the AHS. It is also assumed that drivers traveling on a manual interchange are completely engaged in the driving task.

B. Ran, S. Johnson, S. Leight, Department of Civil and Environmental Engineering, University of Wisconsin at Madison, 2256 Engineering Hall, 1415 Engineering Drive, Madison, Wis., 53706. J. H.-S. Tsao, PATH Institute of Transportation Studies, University of California at Berkeley, Richmond Field Station, Building 452, 1357 South 46th Street, Richmond, Calif. 94804.

The concept of an AHS is being investigated because it may have the potential to offer capacity and safety gains without requiring a significant amount of right-of-way acquisition. However, it may need a significant modification to the current highway infrastructure. Particularly acute is the issue of the infrastructure necessary to support continuous automated driving between two crossing highways. Tsao et al. (*2*) pointed out that eight extra highway-to-highway connector ramps, in addition to the eight existing highway-to-highway connector ramps for the conventional manual traffic, are required if continuous automated driving (through the interchange) is to be supported for all automated traffic approaching the interchange. Such highway-to-highway interchanges provide not only much comfort but also high throughput capacity between two crossing highways, without which severe traffic congestion may result.

Recognizing the importance of supporting continuous automated driving at the interchanges and the potential complexity of design, Tsao (*3*) proposed a staggered-diamond design for the eight additional automated connector ramps. (The design works equally well for providing eight high-speed turning movements for the HOV traffic at a highway-to-highway interchange.) The design requires only four, instead of eight, separate structures, each supporting two-way traffic. He also discussed the constraints of this proposed interchange design on the conceptual design and evolution of AHS. Note that the constraints would be much more acute if the proposed staggered-diamond design is replaced by eight separate structures, each supporting only one-way traffic. Although variations of this design exist, the idea of consolidating two ramps carrying traffic of opposite directions into one physical structure is robust enough for various geometric configurations and limitations. That design greatly reduces the structural complexity of the eight separate connector ramps and increases the feasibility of AHS.

To support high-throughput and high-speed highway-changing traffic in the urban areas, highway-to-highway interchanges in such areas tend to be multilevel already. Even with the staggered-diamond design, building the four additional physical structures at an area that has already a high degree of geometric complexity may be difficult or very costly. This situation provides an interesting dilemma for AHS developers.

This paper concentrates on this dilemma and studies the impact of the lack of direct connector ramps on the manual and AHS traffic in the manual lanes of traffic. The pros and cons associated with provision of such connect ramps are stated briefly, the methodology for the throughput analysis is explained, and the results are reported.

PROS AND CONS OF PROVISION OF AUTOMATED CONNECTOR RAMPS

This section addresses the issues associated with providing the direct connector ramps for supporting continuous automated driving between two crossing highways as well as those associated with no provision.

No Provision: Major Issues

If no direct automated highway-to-highway connector ramps are provided, then the following issues may cast serious doubt about the ability of AHS to provide high system throughput and solve highway congestion problems:

- Excessive weaving at the interchange area may result because of the likely large amount of highway changing traffic through the manual lanes.
- Expansion of headways for highway-changing traffic that must shift from automated to manual mode will cause a surge of space requirements. Recall that, to achieve high lane throughput, automation will reduce average vehicle headways. As this traffic comes under manual control, conventional headways will need to be reestablished, requiring space for vehicle dispersion or queueing.
- To support the large amount of highway-changing traffic, additional manual highway-to-highway connector ramp lanes will be needed.
- If check-in (for checking vehicle fitness for safe automated operation considerations) is required each time an automation-equipped vehicle desires to enter the AHS, and check-out (for checking the driver's readiness to resume control) is required each time an automated vehicle desires to exit the AHS, the associated delays will exacerbate traffic congestion.
- If a continuous transition lane is required at and near the interchange area (between the manual lanes and the dedicated automated lanes for automation-equipped vehicles to switch between the manual and the automated operating modes), then such a lane will consume much space. However, if a transient transition lane (one that is restricted to the entry/exit areas) is used, the large amount of merging required at the end of the transient transition lane will create turbulence in the traffic stream and may create congestion and safety hazards.
- Assuming a fixed ratio of highway-changing traffic over the through traffic, the higher the mainline AHS throughput, the more serious the congestion could be.

Provision: Major Issues

Provision of the direct automated highway-to-highway connector ramps involves the following design and cost issues:

- Expanding the interchange infrastructure to accommodate eight automated connector ramps in addition to the eight existing conventional connector ramps could be very complex and costly, especially at locations with high geometric complexity. Furthermore, additional right of way could be required.
- Although a common design for conventional highway-to-highway interchanges has the configuration of a cloverleaf, which involves only two levels of structures, it tends to slow traffic and hence hinder traffic flow because of its sharp curvature. Therefore, most urban highway-to-highway interchanges are equipped with ramps that are much straighter in order to support high-speed driving from one highway to another. However, such interchanges usually involve multiple levels of physical structures. Building eight additional connector ramps can be complex or costly, even with the four separate structures proposed by Tsao (*3*).
- If the AHS lanes are elevated above grade in the urban area and if these lanes are also elevated near and at the highway-to-highway interchange area, then the design of such direct automated highway-to-highway connector ramps may be even more complicated.

ANALYSIS METHODOLOGY

To study all the effects pointed out previously, a number of sophisticated models that do not now exist would be required. This paper, therefore, looks at one example of the issue, a cloverleaf design interchange without dedicated connector ramps. The goal of this paper is to give the reader an idea of the magnitude of transferring flow that might be reasonable before dedicated automated ramps would be required with the assumed AHS configuration.

The variables for the input to this analysis include different combinations of traffic volumes. The output, which is presented in a series of charts, includes speeds at key points in the interchange. The subsequent results demonstrate the level of service of the interchange under varying conditions.

Highway Capacity Manual and Software

The *Highway Capacity Manual* (*HCM*) (*4*) and the related Highway Capacity Software (HCS) generally are recognized as standard tools for evaluating conventional highway segments. This study uses the HCS Release 1.3 to evaluate freeway ramp junctions and weaving sections. The application of the HCM methodology for this study is appropriate because this analysis considers only the conventional portions of the interchange and treats the automated portions as inputs into the conventional traffic stream. It is assumed that vehicles will check out from the AHS before entering the interchange and will check in to the AHS only after passing through the interchange. Furthermore, it is assumed that these operations are performed on the fly at high speed so that the vehicles do not have to stop, and thus there is no effect on interchange operation. This paper, therefore analyzes the effect of manual merging, diverging, and weaving movements on only the conventional operation of the interchange.

Model Assumptions

Many assumptions about the infrastructure and traffic characteristics need to be made to use the HCS. The first assumption is that operation under the ideal conditions, as stated in the HCM (*4*), follow: 0 percent grade; 3.6-m lanes; no buses, heavy trucks, or recreational vehicles; adequate clearance of obstructions from driving lanes; and ideal weather conditions. Another important assumption is the configuration of the highway-to-highway interchange and the two highways near the interchange. Although such configurations are site-specific, this paper uses a generic configuration that is discussed in detail in the next section. This layout assumes two through lanes for manual traffic, one dedicated AHS lane, a transition lane, and an additional weaving lane in the loop weaving section (Figure 1). Although automated interchanges may have many configurations, this configuration is used to give a representative example of the operation for this concept at an AHS-to-AHS interchange.

ANALYSIS

As stated before, this analysis uses HCS. The methods described in *HCM* (*4*) are used to analyze freeway ramp junctions, simple freeway weaving sections, and loop ramp weaving sections. Figure 1 shows the geometrics of the interchange that is analyzed.

The only inputs that are changed during this analysis are the ramp volumes and the freeway through volumes. The following defines what parameters are used in each step of the analysis:

1. For the freeway weaving sections (Areas 2 and 6 in Figure 1), the inputs needed are the freeway nonweaving vehicles, up-weaving vehicles, and down-weaving vehicles. This study assumes Weaving Type C, in which the AHS vehicles using the interchange are down-weaving vehicles, the manual through traffic consists of up-weaving vehicles, and the AHS traffic consists of nonweaving vehicles (*4*). In this arrangement, transferring AHS vehicles would check out from the AHS and assume conventional driving responsibilities all the way through the interchange, until they check in again at another AHS lane.

2. In the loop ramp weaving section, Type A weaving is assumed. In this case, the through vehicles on the freeway are the nonweaving vehicles; the vehicles leaving on the off-ramp are down-weaving; the up-weaving vehicles are those that enter on the on-ramp (*4*).

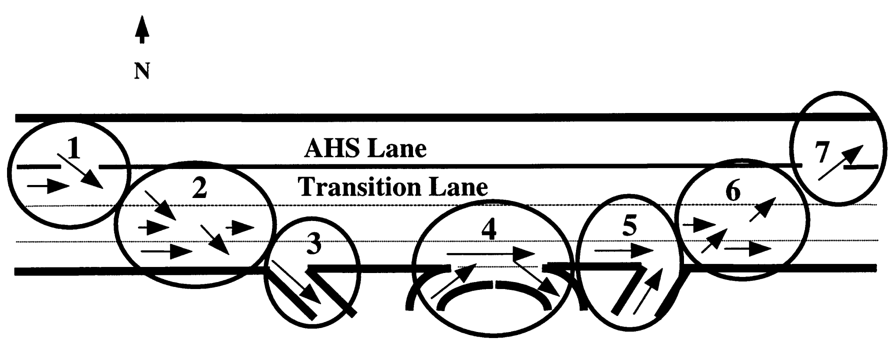
It should be noted that in the discussion of Type C weaving areas, *HCM* strongly recommends against using the type of configuration assumed for this paper, which forces drivers to enter traffic on one side of freeway, weave through all lanes of traffic, and exit on the opposite side of the freeway. However, in the case of no provision of automated ramps, this may be the only possible configuration for this movement. It should also be noted that automated ramps may be required for some movements on interchanges and not others (i.e., heavy east-to-south movements may require a ramp on which light east-to-north movements may not require added capacity.)

Levels of Service

HCM describes the conditions on roadways using levels of service (LOS), which range from LOS A (free flow) to LOS F (breakdown). Table 1 presents brief definitions of the levels of service.

AHS Check-Out and AHS-to-Manual Merging

AHS check-out and AHS-to-manual merging (Figure 2) will be conducted by all exiting AHS traffic. This AHS traffic enters a transition lane that can be occupied by only AHS traffic. This evaluation assumes that only AHS vehicles can enter the transition lane. Even



1 - AHS CHECK OUT and AHS TO MANUAL MERGING
2 - AHS TO INTERCHANGE WEAVING
3 - EXIT RAMP
4 - LOOP RAMP WITH ADDITIONAL WEAVING LANE
5 - ON RAMP
6 - INTERCHANGE TO AHS WEAVING
7 - CHECK IN and MANUAL TO AHS MERGING
– East to south AHS traffic must execute moves 1, 2, and 3.
– East to north AHS traffic must execute moves 1, 2, and 4.
– North to east AHS traffic must execute moves 5, 6, and 7.
– South to east AHS traffic must execute moves 4, 6, and 7.

FIGURE 1 Cloverleaf interchange design.

TABLE 1 LOS Definitions

LOS	Ramp Junctions		Weaving Sections	
	Max Density pc/km/ln	Description	Min Avg. Weaving Speed (kph)	Min Avg. Non-Weaving Speed (kph)
A	6.2	Unrestricted operation	88.6	96.6
B	12.4	Minimum turbulence	80.5	86.9
C	17.4	Average speeds decline	72.5	77.3
D	21.7	Intrusive turbulence	64.4	67.6
E	>21.7	Approaching capacity	56.4/48.3[a]	56.4/48.3[a]
F	-	Unstable operation	<56.4/48.3[a]	<56.4/48.3[a]

[a] 56.4 kph used for computed speeds, 48.3 kph for field - measured speeds

though this is an exiting maneuver, it is treated as an on-ramp with an added lane because the AHS traffic is entering the main traffic flow. From this transition lane, the AHS traffic may then start to weave toward the appropriate exit. This example assumes that the check-out procedure from AHS is done on the fly so that it has no effect on traffic. If this is not the case, the facility may have to be very large to provide for adequate flows. The transition from automated traffic to conventional traffic will cause a dramatic reduction in capacity because of required decrease in vehicle density for human driving, and any significant exiting flow may cause a disruption in flow on the mainline AHS as vehicles attempt to exit. Additional lanes may be required to add capacity to this portion of the interchange area to allow for the transition from automated to conventional driving. The number of lanes will vary with AHS design and local traffic conditions, but a reasonable estimation might be that one lane must be added for every 1,500 to 2,000 vehicles exiting the AHS.

The need for additional required lanes presents an important point. If it is assumed that the AHS carries 4,000 vehicles during the peak, and 50 percent of those vehicles wish to transfer, then at least one lane in addition to the AHS and the transition lane will need to be added to provide adequate throughput capacity in the conventional traffic stream.

Figure 3 shows the levels of service for various combinations of traffic volumes at an onramp with an added lane. The results assume two through lanes before the ramp, before another lane is added at the ramp. The ramp is also assumed to have one lane. Note that any exiting flow greater than 1,700 vehicles per lane per hour (vplph) will cause LOS F, even with very little through traffic. Although 1,700 vplph would be considered heavy traffic for many conventional interchanges, it could be normal to light traffic on AHS interchanges where the mainlines may carry up to 6,000 vplph (*5*).

AHS-to-Interchange Weaving

All transferring AHS traffic will execute the weaving maneuver as shown in Figure 4. Figure 5 shows levels of service for weaving sections of 762.5 m (2501.6 ft) in length. Note that 762.5 m is the maximum length of weaving sections considered by HCS. The plots for the possible flows show that these interchanges break down under very small flow rates. The cloverleaf design in conventional design is much more tolerant of large flows than the automated example shown here because in conventional design, few vehicles are actually required to weave through the main traffic stream. In an AHS with a dedicated left lane, however, this is not the case. An AHS of this design will require all vehicles wishing to transfer to weave through the main traffic stream.

The capacity of weaving sections is a result of length and number of lanes. In shorter weaving sections, more lanes will be required to increase capacity and maintain the level of service. However, adding lanes will make the weaving process more difficult for drivers that must cross all lanes of traffic. Longer weaving sections require fewer lanes to be added to account for weaving capacity loss. Additional capacity (lanes), however, may still need to be added in this area to account for the added AHS vehicles.

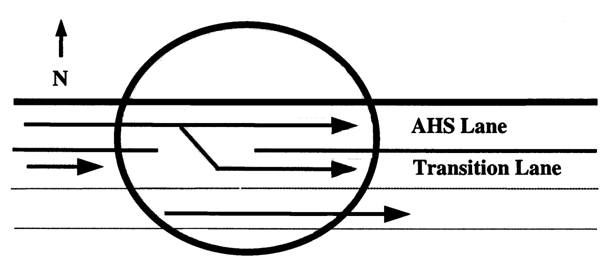


FIGURE 2 AHS check-out and AHS-to-manual merging.

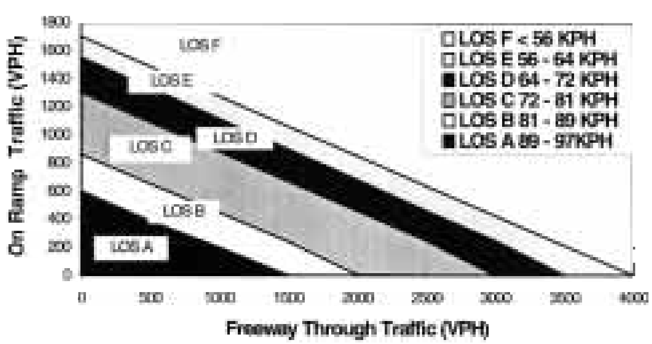


FIGURE 3 LOS for on-ramp with added lane.

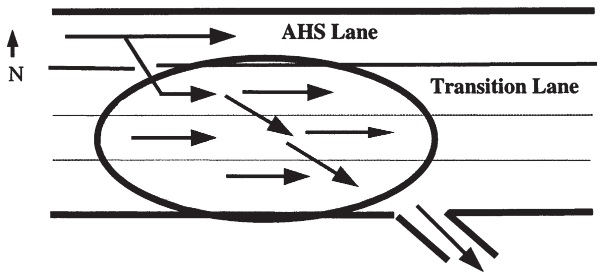


FIGURE 4 AHS-to-interchange weaving.

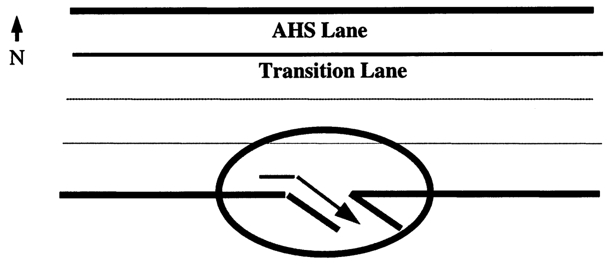


FIGURE 6 Interchange off-ramp.

Figure 5 makes a valid point. Any significant combination of volumes of transferring AHS traffic and manual through traffic would result in heavy congestion or failure in the manually driven weaving area. Under the "no provision for automated ramps" condition, there are some possible actions that could be taken to improve the situation. One may be to further lengthen the weaving section to allow more time for vehicles to weave. However, in many urban environments, moving the AHS entrance to the manual lanes more than a kilometer upstream of the beginning of the interchange might infringe on a previous interchange. Another possibility is to add more lanes to the weaving area, allowing traffic to spread out more. However, this would also increase the number of lanes that weaving vehicles must cross, and dramatically increase cost and environmental concerns, which is one of the reasons the no provision for automated ramps choice is considered in the first place.

Interchange Exit

A one-lane ramp has a capacity of about 1,700 vehicles per hour (vph). If more capacity is required, then more lanes must be added. For this example, this ramp will service east-to-south transfers. This exit should not create a bottleneck if the corresponding on-ramp to the southbound freeway can absorb the required traffic volume.

Figure 6 shows the off-ramp exiting movement. Automated systems are not involved in this portion of the example. Thus, the evaluation can easily be compared to conventional systems. The flow in this example is constrained not by the ramp itself but by the ability of the downstream flow to absorb it. This portion, therefore, is not a critical area in the analysis, because it represents the situation encountered in Area 5 (Figure 1.) This analysis assumes that Area 5 (Figure 1) for the crossed freeway will control the mainline flow at Area 3 (Figure 1.)

Loop Ramp Weaving

Figure 7 shows the geometrics and weaving problems shown in the loop interchange. The results of the weaving analysis are shown in Figure 8 as levels of service associated with various combinations of traffic volumes for a 305-m (1,000-ft) loop ramp weaving section. In this example, there are two manual through lanes, plus an extra lane between the on-ramp and off-ramp portions of the loop.

In this example, this combination of ramps will service east-to-north and south-to-east traffic movements. Once again, the graphs show that any significant combination of through traffic and loop ramp traffic will severely disrupt traffic flow. Recall that in the no provision for automated ramps situation, these ramps are shared by AHS and non-AHS traffic. Today, many of these ramps are already congested. The possible influx of AHS traffic to this situation would worsen the situation.

Interchage On-Ramp Merging

For this example of interchange on-ramp merging (Figure 9), this ramp will service north-to-east transfers. Figure 10 shows levels of

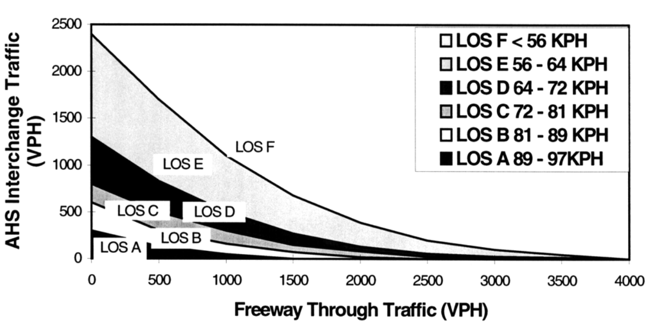


FIGURE 5 LOS for 762.5-m (2,501.6-ft) weaving section.

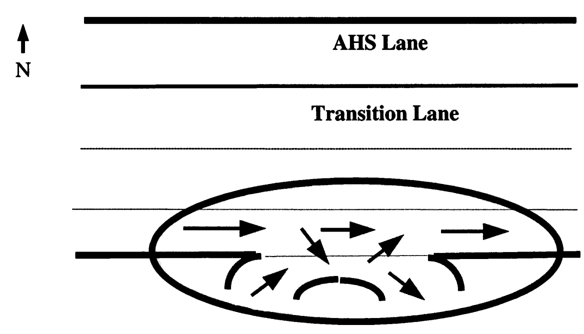


FIGURE 7 Loop ramp weaving.

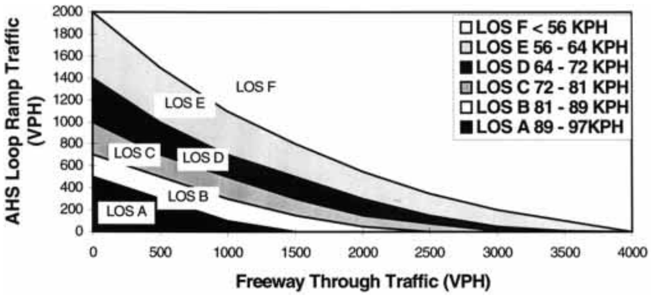


FIGURE 8 **LOS for 305-m (1000-ft) loop ramp weaving section.**

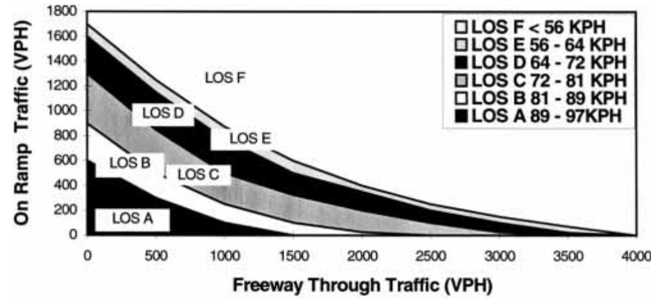


FIGURE 10 **LOS for on-ramp with no added lane.**

service for combinations of traffic volumes at an on-ramp with no added lane. This differs from the very first on-ramp in that a lane is not added for the ramp traffic. Instead, vehicles must merge with the mainline freeway.

As can be seen, it takes a smaller volume of traffic to reach any of the levels of service for this ramp than it would for the first on-ramp, which has an added lane. Once again, volumes that are likely to be seen on this type of ramp with the addition of AHS, such as 1,000 vph in combination with 1,500 vph on the freeway, would bring the freeway to unstable operation (LOS F). On the other hand, lanes can be added to the freeway, but this increases the cost.

Interchange-to-AHS Weaving

Interchange-to-AHS Weaving is shown in Figure 11; the results for this situation should be similar to those in Figures 4 and 5.

Check-In and Manual-to-AHS Merging

Check-in and manual-to-AHS merging is shown in Figure 12, and the key for this maneuver is the check-in process. The best scenario would be for the check-in to be on the fly, so that vehicles do not have to stop. However, if the check-in process requires vehicles to stop, or even slow down, there must be a large storage facility so that there is no spillback onto the manual freeway. If either of these is the case, then this situation would be similar to that of an off-ramp, where capacity shortages could be addressed by adding extra lanes on the ramp. However, note that the location of the check-in area is adjacent to the mainline traffic lanes. This design makes storage vehicles for check-in difficult and may not be feasible.

CONCLUSIONS

The issue of whether to provide direct automated highway-to-highway connector ramps is complex. Both options have significant benefits and drawbacks. Providing such connector ramps would appear to cost more. But not providing them has the potential of greatly exacerbating the already-serious congestion problems at busy interchanges.

The results from this study confirm the potential need for dedicated automated interchange ramps. This paper shows that any moderate to heavy highway-changing traffic may severely disrupt the flow of through traffic, seriously exacerbate congestion at interchanges, and possibly cause a traffic breakdown at the interchange area. These effects will likely negate any throughput benefits for which AHS is designed. The reader is reminded that these results are based on a cloverleaf interchange with two manual through lanes, one automated through lane, one transition lane, one-lane ramps, and one extra weaving lane in the loop ramp weaving section. Although interchange configuration tends to be site-specific, this study selected a representative configuration. The paper shows that the weaving effects encountered when dedicated automated ramps are not provided are severe at a cloverleaf design, where the ramps would be most easy to build. Although the effects of weaving may not be as severe in high-speed interchanges, these areas might be most difficult to provide for separate ramps. A detailed site-by-site study should be conducted for these areas to see if dedicated automated ramps would be needed.

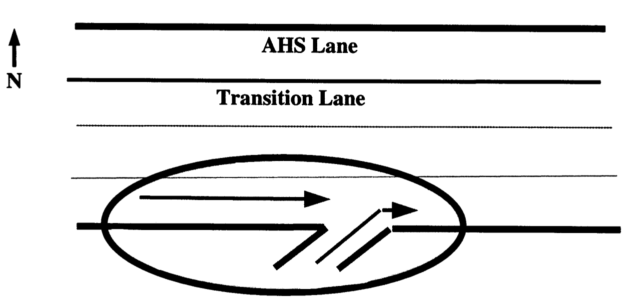


FIGURE 9 **Interchange on-ramp merging.**

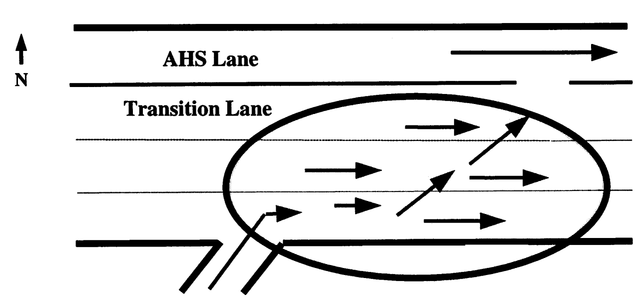


FIGURE 11 **Interchange-to-AHS weaving.**

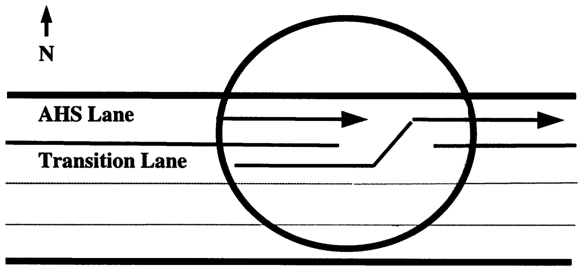


FIGURE 12 Check-in and manual-to-AHS merging.

ACKNOWLEDGMENT

The suggestions on AHS research directions by Steven Shladover at the PATH Program at the University of California at Berkeley are greatly appreciated.

REFERENCES

1. Stevens, W. B. Goals and Definitions of Automated Highway System Concepts. *Proc., 4th Annual Meeting of IVHS America* Atlanta, Ga., April 1994.
2. Tsao, J. H.-S, R. W. Hall, and S. E. Shladover. Design Options for Operating Automated Highway Systems. *Proc., Vehicle Navigation and Information Systems Conference*, Oct. 1993.
3. Tsao, J. H-S. A Staggered-Diamond Design for Automated/Manual-HOV Highway-to-Highway Interchanges and Constraints on AHS Design for Accommodating Automated Highway Change. *IVHS Journal*, Vol. 2, No. 3, 1995, pp. 281–292.
4. *Special Report 209: Highway Capacity Manual*. TRB, National Research Council, Washington, D.C., 1994.
5. Ran, B., and J. H.-S. Tsao. Traffic Flow Analysis for an Automated Highway System. Presented at 75th Annual Meeting of the Transportation Research Board, Washington, D.C., 1996.

Publication of this paper sponsored by Task Force on Automated Highway Systems