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Entrance Capacity of an Automated Highway System

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This paper evaluates the entrance capacity and queueing delay for Automated Highway Systems through use of simulations and analytical modeling. Queueing statistics are also used to determine the sustainable capacity of alternative concepts, taking trip length distribution and spacing between ramps into consideration. Based on safety-spacing headways (produced in a separate analysis), the most promising concept utilizes platoons both on the highway and on on-ramps. However, it is unclear whether comparable capacity can be achieved on exit, when vehicles must be decoupled from their platoons, and whether it is safe for vehicles to enter the highway in closely spaced platoons. The analytical evaluation indicates that entrance/exit spacing on the order of one per 2 km or closer would be required to support highways with total capacity on the order of 20,000 vehicles per hour. Most likely, this would be achieved most efficiently if separate dedicated entrances are provided for automated vehicles, to minimize weaving on manual lanes.

Introduction

Automated highway systems concepts have been developed in the United States under the National Automated Highway System Consortium (NAHSC). One of the tasks facing NAHSC was to select a limited set of automated highway concepts as the focus of future development efforts. Proposed concepts differ in several respects, including vehicle following rules (platooned versus non-platooned), vehicle-vehicle communication and ramp metering. These characteristics affect both the safety and capacity of the highway, as well as the ability of the highway to accommodate future demand.

The purpose of this paper is to compare alternative automated highway system (AHS) concepts with respect to a single dimension: highway entrance delay and capacity. Entrance capacity is one of several

important factors in selecting a capacity, others including safety, deployability, and mainline capacity. Separate analyses have been conducted with respect to these and other AHS criteria. Five concepts were considered by the National Automated Highway System Consortium (NAHSC 1997):

Independent Vehicle. "Fully autonomous vehicles are capable of driving in and around manually driven vehicles on all freeways, and provide limited capabilities such as obstacle and lane departure warning for use on arterials and local streets." (p. A-2) Vehicles do not travel in platoons and there is not infrastructure for controlling vehicle trajectories.

Cooperative. "Vehicles use on-board sensors and computers to drive, and share information among other AHS-equipped vehicles so they can coordinate their motion for safety and high throughput." (p. B-1)

Infrastructure Supported. "Vehicle and infrastructure communications are used to simplify sensor requirements ... This requires standardized inter-vehicle coordination protocols, that eliminate aggressive or drunk driving and reduce chance phenomena such as pinch maneuvers in lane changing." (p. C-1) Vehicles travel in platoons on isolated lanes.

Infrastructure Assisted. Similar to infrastructure supported, except that two-way communication and transmission of precise vehicle and gap locations are used to assist in entry, exit and merge.

Adaptable. Concept is intended to operate in different modes at different locations. At any given time, it would possess characteristics of one of the other four concepts.

Different concepts are likely to produce different capacities due to the way that traffic is organized and controlled. For example, organizing traffic into platoons results in less frequent, but larger, gaps in the mainline traffic stream. This naturally affects the queueing characteristics of vehicles waiting to merge onto the highway. Communication also affects the ability of vehicles to forecast the arrival of gaps. Under the infrastructure-assisted and infrastructure-supported concepts, it is possible to release vehicles from a ramp meter in synchronization with the arrival of gaps, eliminating the need for vehicles to seek out gaps from a merge lane.

The paper develops two models to evaluate entrance capacity and delay: a macro-scale analytical model and a queue simulation model. Queueing statistics from the simulation model are used to estimate the sustainable highway capacity of alternative concepts, taking trip length distribution and spacing between ramps into consideration. The paper makes no attempt to model the AHS as an integrated system, including such issues as lane assignment and platoon formation, as in Broucke and Varaiya (1995) and Hall (1995, 1996). The paper also does not explore strategies for sorting vehicles on entry, prior to their release. Rather, the goal is to develop relatively simple deterministic and stochastic models that enable rapid analysis of a critical AHS element.

The remainder of the paper is divided into four sections, covering prior research, the analytical model, the simulation model and conclusions.

1. Literature Review

The literature on AHS has expanded greatly in recent years due to two programs funded by the United States government: (1) AHS Precursor System Analysis Program, and (2) National Automated Highway System Consortium (NAHSC). Unfortunately, most of the findings under these programs only appear in report format. Furthermore, most of these reports focus on system integration and institutional issues, rather than questions of capacity. The most relevant papers resulting from the federal effort present alternative system concepts, and dimensions for defining alternative system concepts. These include Hall (1996a), Stevens (1993) and Tsao et al. (1993). In these papers, system concepts are defined by such elements as: (1) platooning strategy, (2) existence of barriers separating lanes, (3) mixing of vehicle classes and types, (4) distribution of intelligence, and (5) deployment strategy.

The earliest systematic study of automated highway capacity appears to be the paper by Rumsey and Powner (1974), which examined a moving-cell operating concept. Recently, however, the interest in automated highways has focused more on the platooning concept, as introduced by Shladover (1979). Shladover developed capacity estimates based on a variety of safety criteria, in which the objective was to prevent severe collisions. In a related paper, Tsao and Hall (1994) compare the platooning concept to a "non-platooning" concept (i.e., vehicles do not travel in clusters), and conclude that platooning leads to more frequent small collisions, but less frequent severe collisions. Neither paper analyzed the effects of lane changes. At a more detailed level, vehicle control rules have been investigated, to determine the effects of vehicle performance characteristics on lane-following behavior. The capacity of automated highways with platooning and lane changing has been investigated by Rao et al. (1993), Rao and Varaiya (1993, 1994), and Tsao et al. (1993). All of these utilize the SmartPath simulator developed by Eskafi and Varaiya (1992). SmartPath is microscopic, and models the system down to the level of exchange of messages between vehicles. Tsao et al. (1993), along with Tsao et al. (1996), also include stochastic/analytical models

to represent the time to execute a lane change maneuver and resulting capacity.

Another related direction is research on optimal lane assignment. Hall (1995b) developed a stationary/analytical model that assigns traffics to lanes on the basis of trip length, with the objective of maximizing highway throughput. This is accomplished by minimized capacity losses associated with lane changes. In follow-up work, Hall (1996b) extends the model to highways with varying traffic flows by on ramp and off ramp, through use of a linear programming model. Broucke and Varaiya (1995) created a related model that optimally assigns traffic to lanes, and also optimizes other maneuvers such as platoon formation.

Finally, Hall (1997) developed an analytical model to study capacity within a corridor, with arterials running parallel to an automated highway. This model examines trip lengths and delay as a function of highway spacing, ramp spacing, and capacity concentration.

The research contained in this paper differs from prior research in its focus on the entrance/exit process as a likely system bottleneck. Highway entrance processes have been studied extensively in the context of conventional highways, primarily through empirical analysis. The behavior of individual drivers/vehicles has been studied with respect to their acceleration and gap acceptance behavior (e.g., Kou 1997, Michaels and Frazier 1989, Polus et al. 1985). The aggregate behavior of the traffic stream around merge points has been studied with respect to weaving behavior (e.g., Wang et al. 1993, Moskowitz and Newman 1963, Cassidy and May 1991, Cassidy et al. 1989). Research to date has focused on behavioral modeling, and determining effects of driver behavior on traffic flows.

Because Automated Highway Systems would operate under computer control (with fewer random disturbances and less variation from vehicle to vehicle), the existing conventional models are unlikely to represent AHS behavior. Exiting processes from AHS have been studied by Ran et al., with emphasis on the design of roadway systems around the exit. O'Brien et al. (1994) examined infrastructure aspects of AHS entrances and exits. Our paper is the first to examine the relationship between the AHS concept and delays that occur at AHS entrance.

2. Analytical Highway Model

This section presents an approximate model for determining design requirements for entrance capacity as a function of highway throughput. It represents a first-cut analysis to assess whether a desired highway capacity is attainable. Entrance and exit capacities are evaluated as a function of the spacing between entrances and exits, and their configuration. Two basic configurations are considered in this section: (1) dedicated ramps, which connect directly to manual roadways, and (2) transition lanes, which provide a continuous interface between manual and automated traffic on a highway. Dedicated ramps will be further classified according to the input configuration (to be described later).

In this section, the entrance and exit process are assumed to be symmetric, meaning that entrance capacity is identical to exit capacity. In reality, entrances and exits differ. At entrance, vehicles may be allowed to queue while waiting for a suitable gap on the AHS. At exit, failure to find a suitable gap may result in a missed exit. Furthermore, the transfer of control from driver to computer is inherently different from the transfer of control from computer to driver, perhaps resulting in different capacity on entry than on exit. These considerations will require further analysis in the future. If entrance capacity differs from exit capacity, then the lesser of the two can be used in this analysis.

The analysis also assumes that traffic flows are stationary in time. In one model, flow is assumed stationary across space; in another, flow is assumed to accumulate linearly, then dissipate linearly (as in traffic approaching a central business district). Flow variations over time would result in stricter requirements for entry and exit. Hence, the capacity values derived here are upper bounds.

Capacity, As Measured in "Flux"

The entrance and exit capacities are properly measured in units of "flux;" that is, the maximum rate at which vehicles can enter and exit the highway, per unit length of highway. The analysis assumes that AHS are entered either through dedicated ramps or transition lanes, and not both.

In the case of dedicated ramps, the flux capacity depends on the ramp spacing and on the ramp capacity as follows:

$$\phi = c/l = \text{flux capacity}, \quad (1)$$

where

- c = capacity per dedicated entrance
= capacity per exit,
- l = spacing between dedicated entrances
= spacing between exits.

In the case of transition lanes (i.e., vehicles do not enter and exit at discrete points), the flux capacity can be calculated from the average time that vehicles reside in the lane and the vehicle spacing:

$$\phi = p/2x\tau, \quad (2)$$

where

- x = average separation between vehicles
in transition lane,
- τ = average time that vehicles reside
in transition lane,
- p = proportion of highway length for which
transition lanes are provided.

The parameter 2 is included to account for the combined effect of vehicles entering the AHS and leaving the AHS. If transition lanes provide discrete entrance and exit, their capacity is much like that of a dedicated ramp.

Highways with transition lanes (either uninterrupted or discrete) are further constrained by the capacity of the manually operated on and off ramps entering the highway:

$$\phi_m = c_m/l_m = \text{flux capacity for manual entrances},$$

where

- c_m = capacity per manual entrance
= capacity per manual exit,
- l_m = spacing between manual entrances
= spacing between exits.

Relationship Between Flux Capacity and Lane Capacity

The lane throughput is defined as the maximum rate at which traffic can pass any point in a lane. The throughput for an AHS lane is constrained by the flux capacity, along with the capacity of the lane itself. First, we consider a homogeneous highway, with constant in-flow and out-flow per unit highway length. Because entrance and exit are spread out, this scenario provides the most favorable circumstance for maximizing throughput. Second, we consider the other extreme, where entrances and exits occur in disjoint highway sections. Highway capacity is considerably less, because entrance and exit flows are more concentrated.

Homogeneous Highway. In the case of a homogeneous highway, the throughput per AHS lane is simply the product of the flux and the trip length, divided by the number of lanes. Therefore, taking both flux capacity and lane capacity into account, the maximum throughput equals

$$f = \text{maximum throughput per AHS lane,} \\ \leq \min\{c_l, \phi d/L\}, \quad (3)$$

where:

- c_l = lane capacity,
- d = average trip length,
- L = number of automated lanes.

In the case of transition lanes, throughput is also constrained by the capacity of manual entrances:

$$f \leq \min\{c_l, \phi d/L, (\phi_m d - f_m)/L\}, \quad (4)$$

where

$$f_m = \text{throughput on manual lanes.}$$

The significance of entrance/exit capacity depends on a variety of factors, including the number of lanes on the AHS, the average trip length, and the flux capacity. To generalize, entrance/exit capacity is most likely to be binding in urban conditions, when trips are short and numerous, and constructing entrances and exits is expensive. Entrance/exit capacity is less likely to be binding on inter-city highways.

Non-Homogeneous Highway. The non-homogeneous highway is configured as follows: (1) Start of highway begins with zero flow; (2) Highway is partitioned into an entrance section and an exit section; (3) The entrance section has length l_o and the exit section has length l_d ; (4) Within the entrance section, vehicles enter with constant flux, and exit at rate 0; (5) Within the exit section, vehicles exit with constant flux and enter at rate 0; (6) Constant number of lanes.

This configuration is a limiting case of traffic traveling from residential communities toward a central business district. Returning to dedicated entrances and exits, throughput is calculated as follows:

$$f \leq \min\{c_l, \phi l_o/L, \phi l_d/L\} \quad (5)$$

The maximum throughput is measured at the end of the entrance section/start of the exit section. The maximum *average* throughput over the entire highway is half this quantity, and the average trip length is half the sum of l_o and l_d . Introducing r to represent the ratio l_o/l_d , the maximum average throughput can be expressed as

$$\begin{aligned} f &= \text{maximum average throughput per AHS lane} \\ &\leq (1/2) \min\{c_l, 2\phi d/L \min\{1/(1+r), 1/(1+1/r)\}\} \end{aligned} \quad (6)$$

When r equals 1, f is one-half the throughput of a homogeneous highway. When r differs from 1, the entrance/exit capacity declines. For example, with $r = 3$ (e.g., exits are concentrated, but entrances are disbursed), capacity declines an additional 50%. Capacity would be further restricted in the case of manual entrances, which are not modeled here for the sake of brevity. On the other hand, if the number of lanes varies over the length of the highway in accordance with flow, then per lane capacity would be more similar to the homogeneous case.

Analytical Capacity Estimates for Dedicated Entrances and Exits

The capacity of a dedicated entrance depends on its configuration. Due to the assumed symmetry, only on-ramps are discussed here. Assume that vehicles enter the ramp under manual control, from one or

more lanes, and leave the ramp under automated control, through a single lane. Let

m = number of manual lanes feeding the ramp.

Then:

$$c = \min\{mc_{lm}, c_e, c_a\} \quad (7)$$

where

c_{lm} = capacity per manual entrance lane,
 c_e = entrance capacity of access roadways,
 c_a = capacity for automated portion of ramp.

Even under the most ideal conditions, c_{lm} could be no more than the capacity of a manual highway lane. The Highway Capacity Manual (TRB 1985) states that a single lane on-ramp has capacity of 1700 vehicles per hour at E level (<30 mph) congestion. However, c_{lm} , along with the access capacity, also depend on the interchange configuration, placement of surrounding traffic signals, signal timings and traffic patterns. Under the best of conditions and allowing for two on-ramp lanes, $\min\{mc_{lm}, c_e\}$ might be on the order of 4000 vehicles/hour, with a range of 1000–4000 vehicles/hour being reasonable. The capacity of the automated portion of the on-ramp could be no more than the capacity of an automated lane on the highway itself. However, as discussed in the following section, the capacity is likely to be considerably less.

As a parametric analysis, Figure 1 shows the required on-ramp capacity as a function of the on/off ramp spacing, in order to support an AHS with total lane capacity of 16,000 vehicles per hour (total for all lanes). The analysis is shown for mean trip lengths of 10, 20, 30 and 40 km on a homogeneous highway. As can be seen, for a mean trip length of 20 km (a typical value for urban areas), and an on-ramp capacity of 2,000 vehicles/hour, entrances and exits would be needed at roughly 2.5 km intervals. The required spacing increases as mean trip length increases and as the ramp capacity increases. In an extreme case (as in the prior section), a non-homogeneous highway might require a 50% to 75% reduction in ramp spacing to attain the same *average* throughput.

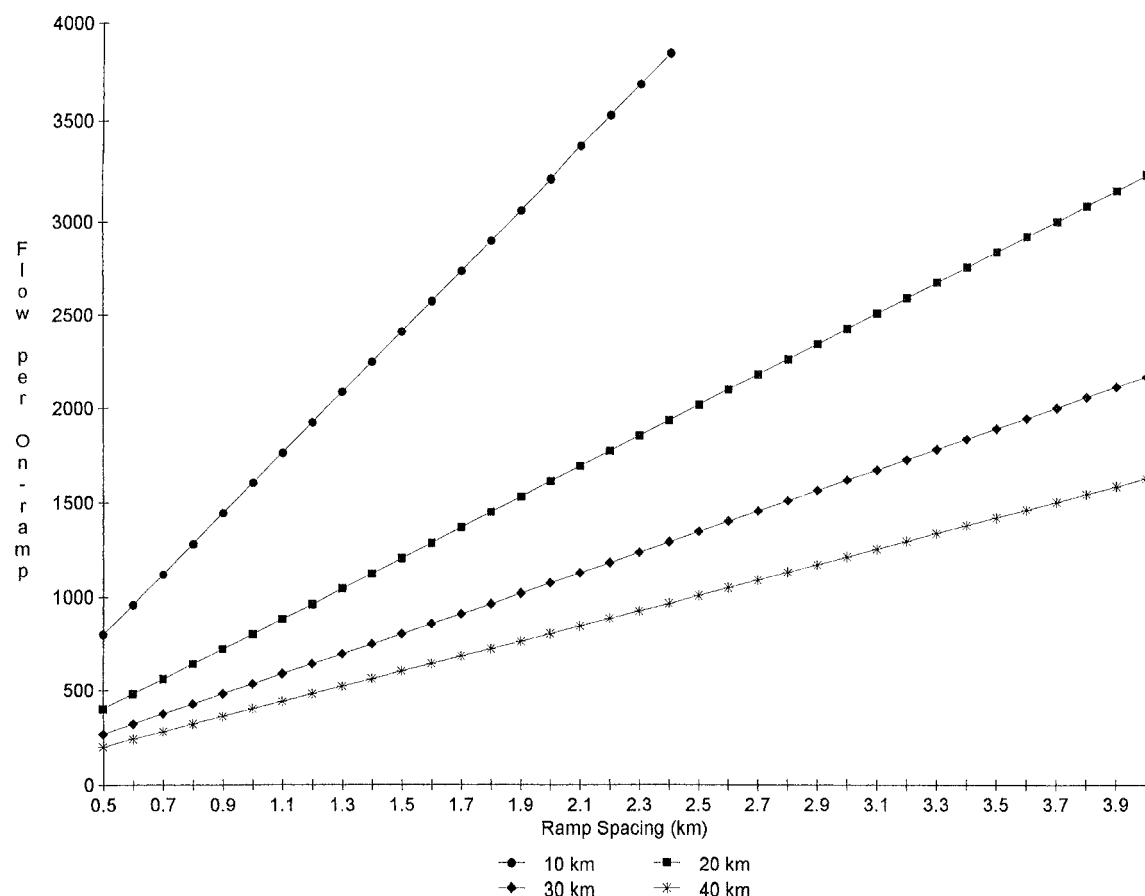


Figure 1 Required On-ramp Capacity as a Function of the On/off Ramp Spacing (16,000 Vehicles/hour)

Analytical Capacity Estimates for Transition Lanes

The transition lane flux capacity is defined by the parameters p , x , and τ . Assume that the average vehicle separation in a transition lane is comparable to the average separation in a manual lane (approximately .05 km). This is appropriate because the transition lane carries vehicles under manual control, mixed with vehicles transitioning to automated control. Then flux capacity takes on the values in Table 1, which into the capacities for lane-throughput in Table 2 (with 2 lanes and an average trip length of 20 km). The transition lane itself does not appear to seriously constrain AHS throughput, assuming that the residency time (τ) is on the order of 30 seconds or less and transition lanes cover at least 50% of the highway's length.

Table 1 Flux (ϕ) (vehicles/km-hr)

	p			
τ (s)	.25	.50	.75	1.0
10	900	1800	2700	3600
20	450	900	1350	1800
30	300	600	900	1200

Table 2 Lane Capacity, Vehicles/hr ($L = 2$, $x = 20$ km)

	p			
τ (s)	.25	.50	.75	1.0
10	9000	18000	27000	36000
20	4500	9000	13500	18000
30	3000	6000	9000	12000

Capacity per Manual Entrance

The capacity of a conventional highway ramp depends on its design. For the most common design, in which the entrance lane directly tapers into a right-hand highway lane, the capacity is roughly 1/2 the capacity of a highway lane, or approximately 1000 automobiles per hour. The capacity can be somewhat larger for designs in which the on-ramp is extended to parallel the right-hand lane, in which case the ramp capacity can approach that of a conventional highway lane (about 2000 vehicles/hour). Capacity can be even larger when multiple lanes are provided at entry. It should be observed that the latter two designs impose additional infrastructure costs, and require substantial purchase of right-of-way. In addition, it may be difficult or impossible to merge traffic into mainline traffic lanes.

According to highway design practice, the spacing between adjacent on-ramps should be on the order of 1 km or larger (Neuman 1993). (However, continuous spacing at such a small interval would likely produce excessive weaving.) At 1 km spacing the flux capacity is limited to 1000–2000 vehicles per km/hour. Hence, the throughput for the entire highway is limited by the values in Table 3.

Within urban areas, average highway trip lengths are on the order of 20 km. Relying on right-hand manual entrances combined with transition lanes would require very close on-ramp spacing with likely excessive amounts of weaving. Taking weaving into account, it may prove infeasible to push the capacity much above the upper limits for conventional highways today. As a matter of highway design practice, non-separated highways rarely are built with more than 5 lanes in each direction, providing a capacity of about 10,000 vehicles per hour. Higher levels of capacity would likely require dedicated AHS entrances.

Table 3 Total Highway Capacity (vehicles/hour) Versus Average Trip Length

Spacing km	10 km	20 km	30 km	40 km
1	10–20,000	20–40,000	30–60,000	40–80,000
2	5–10,000	10–20,000	15–30,000	20–40,000

3. Simulation

A simulation model was developed to evaluate the capacity and delay at an automated/dedicated entrance under a range of conditions. The model is intended for comparison of alternative automation concepts, including communication of vehicle and gap positions between vehicles, organization of traffic into platoons, and ramp metering rules. The model provides statistics on queueing time and distance traveled during merge, all as a function of vehicle arrival rates. By varying the arrival rates on the mainline and ramp, the model can be used to determine the merging capacity of the highway. Unlike more detailed simulators, such as SmartPath, the model allows concepts to be evaluated without coding the specifics of the vehicle control rules and communication.

Overview of Models

The basic model assumes that it is undesirable to disrupt the flow of mainline traffic and that such traffic should move at constant (or nearly constant) velocity during the merge process. However, the model does allow mainline traffic to be organized into platoons of varying lengths, which can be used to improve the efficiency of merging. Ramp traffic is allowed to enter the mainline when gaps of sufficient length appear. The frequency at which these gaps appear and their size, along with the rate at which vehicles arrive on the ramp, dictate the extent of queueing on the ramp and the performance of the system.

As illustrated in Figure 2, the model has four basic elements:

- (1) arrival generator for mainline,
- (2) arrival generator for ramp,
- (3) ramp meter for releasing vehicles from ramp,
- (4) ramp/mainline merge.

The model is fundamentally a single server queueing system, with the merge point acting as the server (or, with metering, two servers in series). However, service times and interarrival intervals are both correlated and behave according to non-standard distributions, making the system difficult to model analytically.

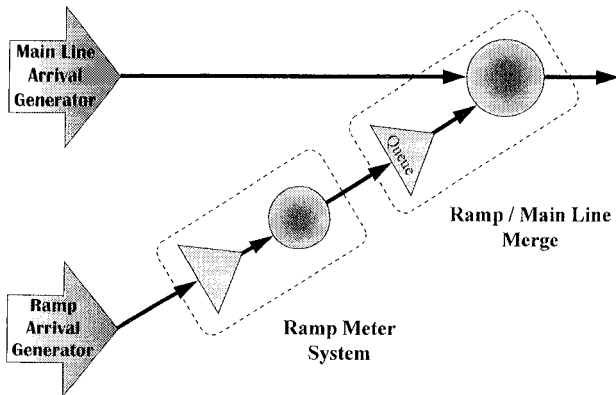


Figure 2 Simulation Model Elements

The model is designed to represent two physical configurations, as shown in Figure 3. In either case, the configuration is limited to a single entrance, including the ramp, merge lane and right-hand land of the mainline. Figure 3a shows the first configuration. Vehicle spacings are inspected upstream from the entrance to determine whether gaps are sufficiently long to accommodate vehicles waiting in the queue. If the gap is sufficient, traffic is released precisely to coincide with the arrival of the gaps on the mainline (called "release to gap"). Traffic only waits in a single merge queue, as it is unnecessary to further meter entry. This case requires communicating precise gap locations to vehicles on the ramp prior to their release.

In Figure 3b, gaps are not communicated to ramp vehicles. Instead, they are released from the ramp meter at a regulated rate and then, upon arrival at the mainline, sense the location of nearby vehicles. If a gap is immediately adjacent on the mainline, then the vehicle immediately moves into position. Otherwise, the ramp vehicle travels along the entrance lane until it locates a gap and then moves over. In this case, the ramp vehicle is assumed to travel at a lower velocity than the mainline. With this lower velocity, the vehicle "waits" for a gap while in motion along the entrance lane.

An underlying assumption of the model is that the travel time from the meter to the mainline merge is a constant value. The value of this constant has no

effect on the queueing characteristics of the system, and is therefore ignored in the analysis. Within this framework, a vehicle is considered "arrived" when it arrives at the point where the mainline and ramp first meet. This is upstream, by a constant value, from the point where gaps are inspected and vehicles are released in the first configuration.

Assumptions and Features

The individual model elements are described below:

Mainline Arrival Generator. Arrival times for mainline vehicles are initially generated by a stationary Poisson process with rate λ_m , reflecting arrivals from upstream. A Poisson process is assumed because it represents vehicles entering the system independently of each other. (However, these times are later modified, as discussed below.) Upon arrival, a length (measured in time) is randomly generated for each vehicle according to a shifted gamma distribution: mean μ_i , standard deviation σ_i and shift parameter m_i . This process yields a data stream of arrival times for vehicle front ends and back ends on the mainline, which are represented by $(x_1, y_1), (x_2, y_2), \dots$

The arrival data must be modified to reflect the vehicle-following rules for the AHS concept (e.g., platooned or not), and to ensure that vehicles do not overlap (the Poisson process does not ensure that $y_i < x_{i+1}$ for all i). This modification could also reflect upstream queueing. The following four parameters depend on the AHS concept (Figure 4a):

- s_1 = intraplatoon spacing (end to front, in time),
- s_2 = minimum interplatoon spacing
(end to front, in time),
- M = maximum platoon size,
- d = "attraction distance" (time).

Note that the spacings are all measured in time. Because the model assumes that vehicles on the mainline move at constant velocity, distance spacing can be converted to time spacing by dividing by velocity.

Let:

- p_i = the position of vehicle i within its platoon (number between 1 and M).

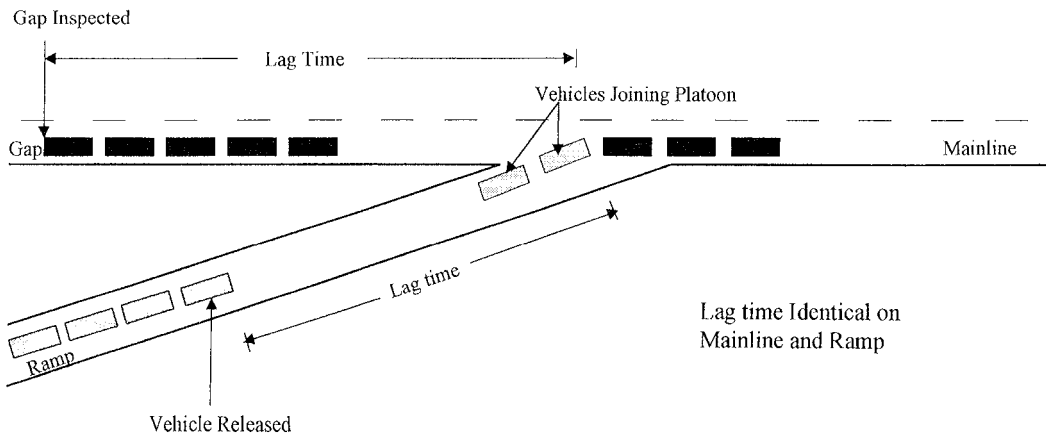


Figure 3a Entrance Configuration When Vehicles Are Released to Fill Gaps

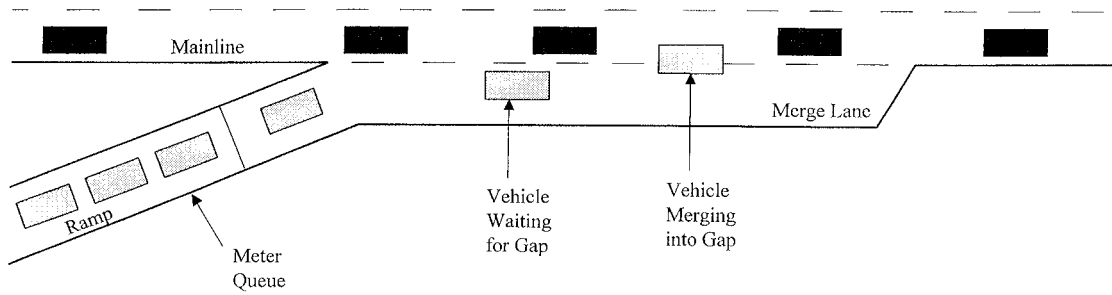


Figure 3b Entrance Configuration When Vehicles Sense Location of Gaps at Entry Point

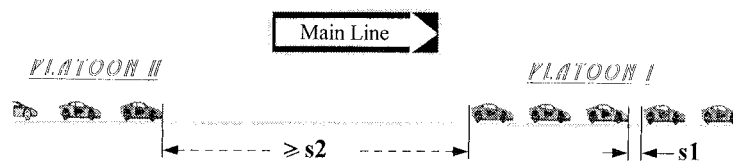


Figure 4a Platoon Spacing Parameters

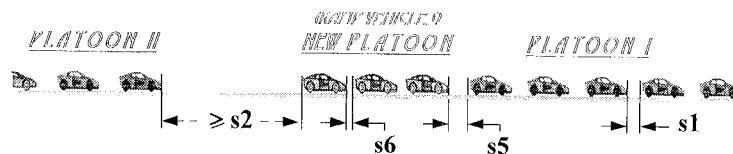


Figure 4b Merge Spacing Parameters

Then vehicles are processed in order of arrival, making the following modifications:

If $p_{i-1} < M$ and $x_i < y_{i-1} + d$:

$$x_i = y_{i-1} + s_1 \quad (8a)$$

If $p_{i-1} = M$ and $x_i < y_{i-1} + d$:

$$x_i = y_{i-1} + s_2 \quad (8b)$$

Otherwise, no adjustment is made. In the model, the attraction distance (d) is the maximum distance from where a vehicle can be "attracted" to the platoon in front of it. The parameter d affects the platoon size distribution, with larger d resulting in larger platoons. In non-platooned concepts, s_1 is set to the minimum intervehicle spacing and M is set to infinity (s_2 can be set to any value). In essence, a non-platooned concept behaves as a platooned concept with infinite platoon size, provided that the intraplatoon spacing is set accordingly. In addition, if the system is purely non-platooned, then d should also be set equal to the minimum intervehicle spacing, meaning that vehicles will not be attracted to their leaders to form vehicle strings (acting as a virtual platoon). Hence, the model can be used to compare platooned to non-platooned concepts, and also to compare alternative high-level control rules for either.

Ramp Arrival Generator. Ramp arrival times are also generated as a stationary Poisson process, and ramp vehicle lengths are generated by a shifted Gamma distribution (identically distributed to mainline vehicle lengths), yielding the data set $(x'_1, y'_1), (x'_2, y'_2), \dots$. Vehicle positions are adjusted to ensure that they are separated by a minimum distance. Let

s_3 = minimum vehicle separation
(back to front, in time), measured at
point where vehicles enter the ramp
under manual control.

Then ramp vehicles are processed in order of arrival to yield $x'_i = \max\{x_i, y_{i-1} + s_3\}$. The model does not set a ramp velocity, and therefore a distance spacing cannot be automatically derived from s_3 .

Ramp Meter. The ramp metering feature is used to regulate traffic entering the highway from the ramp. It is only used in some concepts. The feature is bypassed if the concept releases vehicles to gaps (Figure 3a). Otherwise, metering is an option.

The ramp meter ensures that vehicle spacing equals or exceeds the minimum value:

s_4 = minimum spacing between ramp vehicles
(front to front, time), measured at point where
vehicles are released from the ramp meter.

The ramp meter acts as a single server, first-come-first-served (FCFS), queue with constant service time, which regulates vehicles entering the merge queue. Vehicles are processed in order of arrival, and if $x'_i < x'_{i-1} + s_4$, then x'_i is adjusted to equal $x'_{i-1} + s_4$. The adjustment represents the time in queue. The time in queue and the queue length at the ramp meter are calculated as performance statistics.

Ramp/Mainline Merge. Merging is the most complicated element of the simulator. It inspects the stream of traffic on the mainline to identify gaps that are suitably long to accept ramp vehicles (referred to as an "open gap" hereafter). A vehicle is released into an open gap if a vehicle is present in the "merge queue." Otherwise, the open gap passes the ramp unoccupied. The merge queue forms as vehicles arrive and wait to be served by an open gap. Vehicles are processed FCFS. As mentioned earlier, we assume a constant travel time from meter to merge. Because arrival processes are stationary, the value of this constant does not affect the queueing characteristics. It is, therefore, ignored in the analysis, for the sake of simplicity.

The capacity of the merge depends on the ability to fill open gaps with ramp vehicles in the presence of stochastic variations in vehicle arrivals. The simulator allows for two types of "open gaps": (1) open gaps at the end of a platoon that has not reached its maximum length; and (2) open gaps allowing the formation of a new platoon. An open gap is defined by the parameters s_2 and M (already introduced) along

with the following new parameters (Figure 4b):

- s_5 = minimum spacing between mainline vehicle and entering ramp vehicle (back to front, time).
 s_6 = minimum spacing between adjacent entering ramp vehicles (back to front, time).

These represent the space occupied by the ramp vehicle once it merges into the mainline traffic stream, and are the basis for capacity calculations. If s_5 and s_6 are set to exceed the intraplatoon spacing, then gaps will be closed up after the passing the merge point, and before reaching the next entrance.

Let y_i represent the end of the last vehicle in a mainline platoon, and let x_{i+1} represent the front of the lead vehicle in the trailing platoon. A Type 1 gap is present at the end of the platoon if the following conditions are satisfied:

$$p_i < M \quad (9a)$$

$$x_{i+1} - y_i > s_5 + s_2 + l, \quad (9b)$$

where

l = length of vehicle at front of the ramp queue.

If both Equations (9a) and (9b) are satisfied, and there is a vehicle in the merge queue, then the vehicle is released into the open gap. If one or more vehicles remain in the queue, the gap behind the entering vehicle is also inspected to check if the following conditions are satisfied:

$$p_i < M \quad (10a)$$

$$x_{i+1} - \tilde{y} > s_6 + s_2 + l, \quad (10b)$$

where \tilde{y} is defined as the end of the newly entered vehicle. The substantive difference between Equation (9) and Equation (10) is that s_6 substitutes for s_5 , allowing a different spacing requirement between entering ramp vehicles than between the ramp and mainline vehicles.

Equation (10) is calculated iteratively until one of the following occurs: (1) there is no more space to add vehicles (Equation (10b) no longer satisfied), (2) the platoon reaches its maximum number of vehicles (Equation (10a) no longer satisfied), or (3) the ramp queue is exhausted.

If Case 1 holds, there must also be insufficient space to form a new platoon in the gap, so the simulator finishes processing the gap and proceeds to the gap following the next platoon on the mainline. If Case 2 holds, the gap must then be re-inspected to determine whether there is sufficient space to form a new platoon:

$$x_{i+1} - y_i > 2s_2 + l \quad (11)$$

If Equation (11) is satisfied, the vehicle at the front of the ramp queue is released at time $y_i + s_2$. The trailing mainline gap is then inspected according to Equation (10) to determine whether there is sufficient space to release additional ramp vehicles into the new platoon (iteratively, as above).

In Case 3, the program waits until the next ramp arrival or until the arrival of the next platoon on the mainline (whichever comes first). In the former case, the remaining mainline gap is examined to determine whether sufficient space remains to form a new platoon, in which case the vehicle is released immediately. The program then proceeds to examine trailing vehicles and gaps to see whether additional vehicles can be released. In the latter case (platoon arrives before ramp vehicle), the program proceeds with processing the next mainline gap, following the steps above.

The merge element provides performance statistics on the merge queue, representing waiting time from vehicle arrival until entering the mainline as well as number of vehicles in the queue. The performance statistics directly represent concepts that release vehicles to gaps. The performance statistics can be modified to represent concepts that do not provide communication, as discussed in the following section.

Concepts That Do Not Release to Gaps. In some concepts, ramp vehicles are unable to detect the location of suitable gaps until they are close to or adjacent to the mainline. As a consequence, vehicles cannot be released from the ramp to precisely coincide with gaps. Instead, vehicles travel along the ramp until they are within their "attraction distance" of the mainline, and then travel adjacent to the mainline until a suitable gap is located. In such a system, ramp

vehicles do not queue in the conventional sense, but instead queue while in motion, traveling along an entrance lane adjacent to the mainline (Figure 3b). The entrance lane must be sufficiently long, to allow the great majority of vehicles to enter the mainline under peak traffic conditions. It must also have a way to remove vehicles that are unable to enter and/or have a way to adjust mainline vehicle trajectories to ensure that all vehicles can enter (this might only be done on exceptional circumstances).

With some simplifying assumptions, the simulated merge queue time can be converted to an entrance travel distance, which can in turn be used to set requirements for the length of the entrance lane. We assume that both mainline and ramp vehicles travel at constant, but non-identical, velocities. As a result, gaps approach the ramp vehicle at a speed equalling the difference in their velocities. The ramp vehicles waits in the merge queue until a suitable gap arrives. The distance traveled while waiting for a gap is derived from the following parameters:

$$\begin{aligned} v_m &= \text{velocity of mainline vehicles} \\ v_r &= \text{velocity of ramp vehicles } (v_m > v_r) \\ \Delta &= v_m - v_r \end{aligned}$$

The time in the merge queue for any vehicle, t_i , can be converted into a ramp travel distance by solving for the intersection of the trajectories for the ramp vehicle and the mainline gap:

$$t_i + d_r/v_m = d_r/v_r \quad (12)$$

where

$$d_r = \text{distance traveled on ramp to merge}$$

Equation 12, solved for d_r , yields:

$$d_r = (t_i v_m v_r) / \Delta \quad (13)$$

d_r declines as v_r declines, suggesting that a large velocity differential reduces the entrance lane requirement. Nevertheless, small v_r also makes it more difficult to execute the lane change and increases spacing requirements due to the need to accelerate vehicles in the course of the lane change.

The entrance lane should be sized so that the vast majority of vehicles can gain entry to the highway.

The following section presents a "3-sigma" requirement: entrance lane must equal or exceed the $E(d_r)$ plus three standard deviations. More or less stringent requirements can be set by changing the number of standard deviations, or setting the requirement based on a percentile of the dr probability distribution.

It should be noted that $E(t_i) + 3\sigma$ must be quite small to attain a reasonable design requirement. With $v_m = 30$ m/s (108 km/hr), requirements in Table 4 are shown for two ramp velocities (results are used to illustrate Equation 13, and not to compare different Δ s; different Δ s could result in different waiting times).

Based on these results, a 3-sigma waiting time in excess of 5 s could lead to an unacceptable entrance lane requirement, which implies that *mean* waits as small as 1 to 2 seconds could be problematic. It should be noted that the standard deviation is sensitive to the queue discipline. Assuming that entering vehicles travel at a slower velocity than mainline vehicles, then queued vehicles would encounter gaps in a last-come-first-served sequence (i.e., gaps approach queued vehicles from the rear). This adds considerably to the variation in waiting time, consequently demanding even longer entrance lanes. On the other hand, in some concepts, the attraction might begin some distance before the ramp vehicle reaches the mainline. In such a case, the ramp requirement can be reduced by this distance.

A fundamental difference between communication and sensing based systems is that the former allows vehicles to queue at rest on the ramp, whereas the latter creates a queue in motion. The consequence is that sensing based systems require more lane length to accommodate vehicles waiting for entrance. This requirement can be moderated by utilizing ramp

Table 4 Entrance Ramp Lengths

$v_m = 30$ m/s (108 km/hr) and $v_r = 27$ m/s (97.2 km/hr)

$E(t_i) + 3\sigma$.5 s	1.0 s	2.0 s	5.0 s	10 s
Entrance Lane Length	135m	270 m	540 m	1350 m	2700 m

$v_m = 30$ m/s (108 km/hr) and $v_r = 24$ m/s (86.4 km/hr)

$E(t_i) + 3\sigma$.5 s	1.0 s	2.0 s	5.0 s	10 s
Entrance Lane Length	60 m	120 m	240 m	600 m	1200 m

metering, with the result of somewhat longer total time in queue (counting both the meter and merge queues).

Alternative Simulator. If the autonomous concept allows for some cooperation, then it is possible to reduce the entrance lane requirement. This might be achieved by requiring mainline vehicles to slow to provide sufficient gaps for entering vehicles. This concept was simulated as an alternating service queueing system. Mainline and ramp vehicles enter separate queues, which are served on an alternating basis with deterministic service time (defined by the minimum spacing). In the event that one queue is empty, the other queue would be served continuously until the next arrival in the empty queue. The performance of the system was measured by the mean time in queue for each queue (mainline and ramp). Required entrance lane length was not calculated. This would require a more detailed simulator. Furthermore, no attempt was made to verify that mainline queues would not present safety or operational problems for mainline traffic.

Experimental Design and Parameter Values

A series of experiments was completed to evaluate the automation concepts introduced at the start of this paper. The model does not have sufficient resolution to distinguish between infrastructure assisted and infrastructure supported concepts, so these were treated as a single concept. The model also does not have resolution to distinguish the flexible concept from the others, so this was not modeled. The primary differences between the concepts are as follows:

Infrastructure supported or assisted:

- 1) vehicles travel in platoons
- 2) vehicles are released into gaps

Cooperative:

- 1) vehicles do not travel in platoons
- 2) vehicles are released into gaps

Autonomous:

- 1) vehicles do not travel in platoons
- 2) vehicles are not released into gaps

Spacing values were generated by PATH through use of their safety evaluation tools (NAHSC 1997). In the case of non-platooned concepts, the interplatoon spacing was set identical to the intraplatoon spacing, with arbitrarily large platoon size (platoon size does not affect results with identical spacing). Concepts were defined by the following parameters:

I. Infrastructure Supported or Assisted with Platoons

Modeled as "release to gap".

Maximum platoon size = 10.

Intraplatoon Spacing = 2 m.

Velocity = 20 m/s: Interplatoon Spacing = 29 m;

Attraction Distance = 50 m,

30 m/s: Interplatoon Spacing = 61 m;

Attraction Distance = 80 m,

40 m/s: Interplatoon Spacing = 104 m;

Attraction Distance = 120 m.

Ia: Platooned Entry.

Vehicles enter the highway as platoons, with identical spacings as vehicles already on the highway.

Ib: Free-agent Entry.

Spacing of vehicles entering the highway cannot be less than the interplatoon spacing.

Ic: Modified Platooned Entry.

Vehicles enter the highway as platoons; however, spacing in front of the first vehicle in a platoon cannot be less than the interplatoon spacing.

II. Cooperative Concept

Modeled as "release to gap".

Maximum Platoon Size = 1000.

Interplatoon Spacing = Intraplatoon Spacing.

Velocity = 20 m/s: Spacing = 18 m;

Attraction Distance = 50 m,

Velocity = 30 m/s: Spacing = 38 m;

Attraction Distance = 50 m,

Velocity = 40 m/s: Spacing = 65 m;

Attraction Distance = 80 m.

III. Autonomous Concept

Modeled in two ways:

- a) Metered entry, with LCFS queue at entrance (rate = $1.05 \times$ ramp arrival rate),
- b) Queue on mainline and ramp, with alternating service.

Maximum Platoon Size = 1000.

Attraction Distance = 50 m.

Interplatoon Spacing = Intraplatoon Spacing.

Mainline Velocity = 20 m/s: Spacing = 20 m;
Ramp Velocity = 18 m/s,

Mainline Velocity = 30 m/s: Spacing = 41 m;
Ramp Velocity = 27 m/s.

The experiments had the following common characteristics:

Minimum Vehicle Length:	4.0 m,
Average Vehicle Length:	5.0 m,
S.D. Vehicle Length:	.5 m,
Minimum Spacing on Ramp (s_3)	.25 s.

The primary performance measure for concepts I and II was average time in queue for entering vehicles (by assumption, mainline vehicles do not queue). The primary performance measure of concept IIIa was required entrance lane length. The primary performance measures for concept IIIb were average queue time on mainline and average queue time on entry.

In all of the experiments, the capacity of the highway is maximized when the entry ramp has zero flow. In this condition, the flow is bounded by the following "nominal capacity":

$$\text{Capacity} \leq M/[M(I + s_1) + (s_1 - s_2)], \quad (14)$$

where spacing and length parameters are measured in units of time. Substituting the prior parameter values yields the following *nominal* capacities:

Concept I:

Capacity ≤ 7423 vehicles/hour (20 m/s),
Capacity ≤ 8372 vehicles/hour (30 m/s),
Capacity ≤ 8521 vehicles/hour (40 m/s).

Concept II:

Capacity ≤ 3130 vehicles/hour (20 m/s),
Capacity ≤ 2512 vehicles/hour (30 m/s),
Capacity ≤ 2057 vehicles/hour (40 m/s).

Concept III:

Capacity ≤ 2880 vehicles/hour (20 m/s),
Capacity ≤ 2348 vehicles/hour (30 m/s),
Capacity ≤ 1946 vehicles/hour (40 m/s).

Any vehicle flow on the ramps decreases the nominal capacity in two ways: (1) because of the larger space requirement for vehicles during merging, (2) due to the stochastic element of vehicle arrivals on the ramp. Simulation experiments were completed for various combinations of ramp and mainline arrival rates to measure delays and estimate capacity. Each run covered one hour of operation, and each experiment covered 10 runs. A standard error was computed from the standard deviation among the 10 runs. This was converted to a 95% confidence interval with the t distribution. Simulation results are only provided for combinations of ramp and mainline arrival rates that are in the vicinity of capacity (many more runs were completed than shown).

Numerical Results

Tables 5–10 provide numerical results from simulations. As a general comment, delays become unacceptable when the combined ramp and mainline flows are well below the nominal capacity, as determined by Equation 14. This can be attributed to the following:

- Vehicles cannot be perfectly packed into available gaps because gap lengths are not integer multiples of vehicle lengths, both of which vary continuously.
- Platoon sizes cannot be sustained at the maximum length, due to the random joining process.
- In some scenarios, additional space is required during the entry process.
- Random arrivals sometimes cause gaps to pass unfilled.
- Under the autonomous concept, even small waits can be intolerable.

Table 5a provides results for concept Ia, platooned with platooned merge. The sustainable capacity with the indicated attraction distances is close to 7000 vehicles per hour (ramp and mainline arrival

Table 5a **Platooned with Platoon Merge**

Traffic Volume			Intra-p	Inter-p	Attraction	Average	95% conf
Ramp	Mainline	Velocity (m/s)	Separation (m)	Separation (m)	Distance (m)	Delay (s)	interval (%)
3000	3000	20	2	29	50	25.5	±46
3000	4000	20	2	29	50	1010	±46
3000	3000	30	2	61	80	2.66	±8
3000	4000	30	2	61	80	102	±32
3000	3000	40	2	104	120	4.6	±10
3000	4000	40	2	104	120	119	±28

Table 5b **Platooned with Platooned Merge: Effect of Attraction Distance**

Traffic Volume			Intra-p	Inter-p	Attraction	Average	95% conf
Ramp	Mainline	Velocity (m/s)	Separation (m)	Separation (m)	Distance (m)	Delay (s)	interval (%)
3000	3000	30	2	61	50	169	±26
3000	3000	30	2	61	80	2.66	±8
3000	3000	30	2	61	110	3.82	±10
3000	3000	30	2	61	140	3.56	±7

rates combined), roughly 80% of the nominal capacity. Capacity is somewhat less for 20 m/s, but still approximately 80% of the nominal capacity.

Table 5b shows the effect of attraction distance on delay for a combined arrival rate of 6000 vehicles/hour. When the attraction distance is below the inter-platoon spacing, the system performs poorly. However, once it exceeds the inter-platoon spacing, the attraction distances seems to have little effect on delay.

Table 6 evaluates concept Ib, platooned with free-agent merge. Capacity here (about 2000 vehicles/hour) is much less than platooned merge, due to much longer spacing required of entering vehicles. Also, higher velocities perform worse than lower velocities. This is because each entering vehicle requires more time on entry at higher velocities (e.g., 2.72 s at 40 m/s but just 1.7 s at 20 m/s).

Table 7 evaluates concept Ic, platooned with modified platooned entry. Capacity is somewhat greater than concept Ib, but not nearly as large as platooned merge. At 30 m/s velocity, capacity is somewhat greater than 3000 vehicles/hour. Also note that with total demand fixed, delay is smaller when a larger percentage of the demand is on the mainline than on the ramp (as expected, given spacing requirements).

Table 8 shows delays for concept II. Delays increase at larger velocities, as can be expected because nominal capacity decreases at higher velocity. At 30 m/s, capacity is on the order of 2250 vehicles/hour, comparable to conventional highways, and about 90% of nominal capacity.

Table 9 provides results for concept III. Here, performance is measured as the required entrance lane length. Capacity is very small, on the order of 1000 vehicles per hour at 30 m/s. These values place sustainable capacity in the vicinity of 40%–60% of nominal capacity. This low value is due to the strict requirement that virtually all vehicles be able to enter within a reasonable distance.

Finally, Table 10 shows results for autonomous and mainline slowdown. As expected, the system performs much better than without mainline slowdown. The sustainable capacity is on the order of 2300 vehicles/hour, which is just a few percent below the nominal capacity.

4. Conclusions

Though many questions remain as to the viability of AHS, the study provides some insight into the types of concepts that could potentially provide capacity gains. The simulation analysis clearly indicates

Table 6 Platooned with Free Agent Merge

Traffic Volume		Velocity (m/s)	Intra-p Separation (m)	Inter-p Separation (m)	Attraction Distance (m)	Average Delay (s)	95% conf interval (%)
Ramp	Mainline						
1000	1000	20	2	29	50	13.9	±23
1000	1500	20	2	29	50	137	±33
1000	1000	30	2	61	80	453	—
1000	1000	40	2	104	120	926	—

Table 7 Platooned with Modified Platooned Entry

Traffic Volume		Velocity (m/s)	Intra-p Separation (m)	Inter-p Separation (m)	Attraction Distance (m)	Average Delay (s)	95% conf interval (%)
Ramp	Mainline						
1000	2000	20	2	29	50	5.4	±8
1000	3000	20	2	29	50	22.0	+18
2000	2000	20	2	29	50	74.2	±33
1000	2000	30	2	61	80	18.3	±13
1000	3000	30	2	61	80	433	—
2000	2000	30	2	61	80	496	—
1000	2000	40	2	104	120	157	±37
2000	2000	40	2	104	120	1010	—
1000	3000	40	2	104	120	1150	—

Table 8 Cooperative

Traffic Volume		Velocity (m/s)	Separation (m)	Attraction Distance (m)	Average Delay (s)	95% conf interval (%)
Ramp	Mainline					
1000	1500	20	18	50	8.6	+14
1000	2000	20	18	50	278	+71
750	1500	30	38	50	99.3	±24
500	2000	30	38	50	738	±39
750	1500	40	65	80	919	—
500	2000	40	65	80	1750	—

Table 9 Autonomous: No Mainline Slowdown, Metered Entry

Traffic Volume		Velocity (m/s)	Separation (m)	Attraction Distance (m)	Ramp Requirement (km)
Ramp	Mainline				
250	1000	20	20	50	1.0
500	1000	20	20	50	1.05
1000	1000	20	20	50	2.1
250	500	30	41	50	1.2
500	500	30	41	50	1.3
750	500	30	41	50	1.9

Table 10 Autonomous: Mainline Slowdown

Traffic Volume		Velocity (m/s)	Separation (m)	Attraction Distance (m)	Avg Ramp Delay (s)	Avg Main Delay (s)
Ramp	Mainline					
1250	1000	30	41	50	22.1	7.37
1150	1150	30	41	50	21.3	30.3
750	1500	30	41	50	3.2	21.5

that some concepts will have difficulty in increasing capacity over conventional highways: (1) Infrastructure assisted/supported combined with free-agent entry; (2) Autonomous concept without mainline slowdown under any condition; (3) Either the cooperative or autonomous concept unless spacings can be reduced.

Based on the PATH-determined spacing values, by far the most promising concept is infrastructure assisted/supported with platooned entry. However, it is unclear whether comparable capacity can be achieved on exit, when vehicles must be decoupled from their platoons, and whether it is safe for vehicles to enter the highway in closely-spaced platoons.

Further analysis is needed to study the interaction between entrance and exit processes, possibly allowing for sorting traffic by destination at entrance. Analysis is also needed on mixed vehicle classes and, eventually, more detailed simulation is needed on vehicle dynamics in and around the points of entrance and exit.

The analytical evaluation indicates that entrance/exit spacing on the order of one per 2 km or closer would be required to support highways with capacity on the order of 20,000 vehicles per hour. Most likely, this would be achieved most efficiently if separate dedicated entrances are provided for automated vehicles, if for no other reason than to minimize weaving on manual lanes.

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