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Authors

Hall, Randolph W.
Caliskan, Cenk

Publication Date

1997

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

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Randolph W. Hall

Cenk Caliskan

University of Southern California

California PATH Research Report

UCB-ITS-PRR-97-44

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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Report for MOU 256

November 1997

ISSN 1055-1425

DESIGN AND EVALUATION OF AN AUTOMATED HIGHWAY SYSTEM WITH OPTIMIZED LANE ASSIGNMENT

November 10, 1997

**Randolph W. Hall
Cenk Caliskan**

**Department of Industrial and Systems Engineering
University of Southern California
Los Angeles, CA 90089-0193**

ACKNOWLEDGMENTS

This project was funded by Partners for Advanced Transit and Highways (PATH) and the California Department of Transportation (Caltrans). Jacob Tsao of PATH is thanked for his comments and suggestions.

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ABSTRACT

Highway automation entails the application of control, sensing and communication technologies to road vehicles, with the objective of improving highway performance. It has been envisioned that automation could increase highway capacity by a factor of three. This paper extends earlier research on optimal lane assignment on an automated highway to dynamic networks. A path-based linear program is formulated and solved through a column generation method. The algorithm has been applied to networks with as many as 20 on and off ramps, 80 segments, 4 lanes and 12 time periods.

Keywords: **Automated Highway Systems**
 Lane Assignment
 Link Layer

EXECUTIVE SUMMARY

This is the final report for PATH MOU 256, Design and Evaluation of an Automated Highway System with Optimized Lane Assignment. This project has produced two linear program models for assignment of traffic to lanes, and determining where to change lanes, with the objective of maximizing throughput on an automated highway. The models are based on the notion that each lane change consumes highway capacity beyond what is normally required for continuing straight in traffic lanes. The additional capacity requirement is expressed in units of time-space. For instance, if a lane-change takes 5 seconds, and if the vehicle requires 100 m of additional space during the lane change, then the maneuver consumes 500 m-s of capacity.

The two models developed in the research project have been previously documented in PATH Working Papers 96-2 (LANE-OPT Users Manual) and 97-6 (DYN-OPT Users Manual). LANE-OPT is a static assignment model, which does not account for time of day variations in traffic flow. DYN-OPT is a dynamic model, which allows for time periods, with different traffic flows in each. Both programs model the highway as a series of segments, where each segment is defined by the number of lanes; whether the segment is an exit, entrance or neither; and capacity parameters. Both programs create an MPS formatted linear program file, solve the program with the CPLEX linear program solver, and format the results for analysis.

In a previous PATH working paper under this MOU (96-3, Optimized Lane Assignment on an Automated Highway) the static model LANE-OPT was applied to a series of test cases, with up to 80 segments, 20 destinations and 5 lanes. In all cases, increasing the number of lanes provided decreasing marginal returns, due to the added overhead for lane changes. Also, the benefit of having additional lanes was found to be greatest when the capacity requirement for lane changes is smallest, and when trip lengths are long.

This final report extends earlier research on optimal lane assignment on an automated highway to dynamic networks, providing analysis of test cases with the DYN-OPT model and development of the theory underlying DYN-OPT. DYN-OPT uses a path-based formulation for the linear program, and solves that program through a decomposition method called column generation. The algorithm has been applied to networks with as many as 20 on and off ramps, 80 segments, 4 lanes and 12 time periods. We also provide results for a case-study analysis of the US 101 Hollywood Freeway in Los Angeles.

Qualitatively, the report shows that results for the dynamic model are quite similar to those for the LANE-OPT static formulation. For this reason, and because data and computational requirements are considerably smaller, we conclude that at this state of research, when concepts are still be developed, that LANE-OPT is a more appropriate analysis tool.

1. INTRODUCTION

Highway automation entails the application of control, sensing and communication technologies to road vehicles, with the objective of improving highway performance (e.g., capacity and safety). Some predictions forecast that automation could increase highway capacity by a factor of three, and that capacity increases of this magnitude would greatly reduce highway congestion. Assuming speeds do not change for the present, greatly increased throughput will demand much closer spacings between vehicles traveling on highways. This will, in turn, complicate the process of changing lanes, as vehicles search for suitable gaps to enter new lanes. Furthermore, supplemental spacing may be needed during the lane change process. All of these factors will demand careful control of when and where vehicles change lanes, in order to achieve the envisioned capacity gains.

In prior research, lane-changing has been evaluated through use of analytical models (Hall, 1995b) and through the use of a linear programming model for a static network (Hall and Lotspeich, 1996). This paper extends the prior research to dynamic networks. As in the prior papers, the objective function is to maximize highway throughput without exceeding the capacity of any lane on any segment of the highway. Capacity is expressed in the form of a work-load constraint, allowing separate parameter values for vehicles continuing in a lane, changing into a lane, changing out from a lane, or passing through a lane. Also like prior research, a fixed origin-destination pattern is assumed, expressed on a proportional basis, and the model is deterministic.

The dynamic lane-assignment problem is formulated as a path-based linear program (unlike Hall and Lotspeich, 1996, which is arc based). For computational efficiency, a column generation solution procedure is employed. The program begins with an initial set of paths identified with a static L.P., along with a number of additional paths that are heuristically generated. The dynamic L.P. is then optimized for this limited path set. Next dual variables are used within a set of shortest path problems to generate additional

paths. The process is repeated until the duality gap falls within user-specified tolerance limit.

The remainder of the paper covers prior research, model formulation, computational results and conclusions.

2. LITERATURE REVIEW

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 initial collisions, but less frequent severe collisions. Neither paper analyzed the effects of lane changes, or follow-on collisions.

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 to the level of exchange of messages between vehicles.

Stochastic models of automated highway systems have been developed by Tsao et al (1993) and Tsao et al (1996). These models use approximations to develop probability distributions for platoon and gap lengths and from these distributions develop probability distributions for the distance traveled in executing lane changes. Hall et al (1997) developed a stochastic queueing model to develop delay distributions for vehicles

entering highways for the purpose of comparing alternative automation concepts (e.g. effects of platooning and communication).

The model that follows is most closely related to papers by Hall (1995) and Hall and Lotspeich (1996), in which workload models are developed for throughput analysis. These papers analyzed capacity as a function of the lane-change overhead, which was measured as the time-space requirement for a lane-change. One of the findings was that for large overhead values, adding lanes does not necessarily add to highway capacity, because the entrance lane becomes saturated. The research is also similar to recent reports by Tsao (1996) and Hongola (1996). The reports document dynamic lane-assignment model with workload constraints on lanes/segments. The model differs from our own research in that the models do not use a path based formulation, which also affects the representation of non-integer travel times. Furthermore, neither the Tsao nor the Hongola paper provides computational results. The concept of space-time workload has also been incorporated in Broucke and Varaiya (1996), in which activity plans (covering velocity and assignment of maneuvers) were developed for a single lane highway. Subsequent research has led to the creation of the "SMARTCAP" simulator.

3. MODEL FORMULATION

The AHS consists of a set of highway segments and sets of on-ramps and off-ramps. Each segment contains one or more automated lanes, which are always situated on the left-side of the highway. The AHS may also have manual lanes, which are always situated on the right-side of the highway. The number of lanes can vary from segment to segment. Lane drops and lane additions are assumed to occur on the right-side of the highway (the model is easily generalizable to more complicated structures). The analysis is based on a highway that operates without congestion, with deterministic travel time. In the implementation, we assume that changes in highway volumes have not affect on vehicle speeds, so long as volumes are below capacity.

3.1 Network Representation

As shown in Figure 1 the highway is represented by a flow network. Highway segments are indexed by location and defined by segment type (on-ramp, off-ramp, or neither on-ramp nor off-ramp), length of the segment, number of lanes, and ramp capacity (for segments containing ramps). Nodes are assigned to the end of each lane in each segment, as well as to the start of each on-ramp and end of each off-ramp. On-ramp nodes are source nodes without entering arcs, and off-ramp nodes are sink nodes without

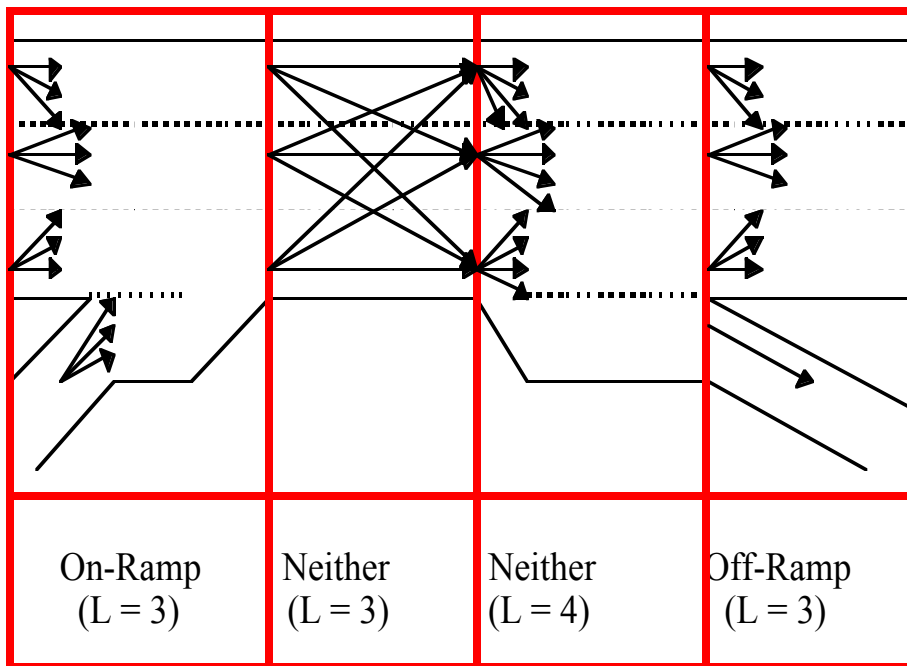


Figure 1: Highway Segments

out-going arcs. Source nodes are also placed at the start of each lane in the first segment, and a "super-sink" node is placed after the last highway segment to absorb all continuing highway traffic. Source nodes at the start of the highway pre-assign entering traffic to a specific lane, whereas the "super-sink" node allows the assignment of continuing traffic to be optimized among lanes (however, in our experiments, the highway was assumed to start with zero traffic).

Each arc represents a vehicle trajectory through a highway segment. A trajectory may entail staying in a lane, transitioning from one lane to another, transitioning from a lane to an off-ramp, or transitioning from an on-ramp to a lane. In each case, the arc is defined by a segment, an initial lane, and an ending lane. For any segment, the graph is completely connected, meaning that vehicles are allowed to transition between any pair of lanes within the segment. The exceptions are source and sink nodes, including on-ramp, off-ramp and super-sink nodes, as well as nodes at the start of the highway. As in Figure 1, arcs that are incident on these nodes only flow in one direction.

The mathematical program uses network flows that are defined on a path basis. Each flow is defined on a path/time-period basis, and represents the total number of vehicles that enter the path per unit time in the specified period. Each origin/destination pair has one or more paths, which are defined by a set of arcs connecting the origin to the destination. The set of available paths is assumed to be identical for all time periods, though this assumption is easily generalized. Let:

$$F_{ijk}(t) = \begin{array}{l} \text{flow on path } k \text{ connecting origin } i \text{ to destination } j, \text{ entering the network in} \\ \text{period } t \\ \geq 0 \end{array}$$

$$d_{ij}(t) = \text{total flow between origin } i \text{ and destination } j \text{ entering in period } t$$

Then for any given time period, the sum of the path flows must equal the total flow traveling between the origin/destination pair:

$$\sum_k F_{ijk}(t) = d_{ij}(t) \quad (1)$$

Capacity constraints bound the flow within each lane/segment. These are bundle constraints, which account for straight traffic (i.e., traffic that enters and exits a segment in the same lane), as well as traffic that enters, exits and passes through each lane within each segment. These constraints are first defined in terms of arc flows. Later, formulas are provided for converting path flows into arc flows. Let:

$$f_{k1l}(t) = \text{flow continuing straight on lane } l \text{ in segment } k \text{ in period } t$$

$$f_{k12}(t) = \text{flow entering lane } l \text{ of segment } k \text{ in period } t$$

$$f_{k13}(t) = \text{flow exiting lane } l \text{ of segment } k \text{ in period } t$$

$$f_{k14}(t) = \text{flow passing through lane } l \text{ of segment } k \text{ in period } t$$

Flow is measured at the start of segments. The symbol z will represent the flow type ($z = 1, 2, 3$ or 4 in above). The total workload is defined as a linear combination of the flow variables, which cannot exceed the capacity of the lane/segment to perform work:

$$\sum_{z=1}^4 \alpha_z f_{k/z}(t) \leq W_{k/l}(t), \quad (2)$$

where α_z is the workload associated with flow type z for a segment (measured in units of time). $W_{k/l}(t)$ represents the capacity of the lane/segment to perform "work" (i.e., carry traffic). The left-hand side of Eq. 2 represents the total time to perform all work in lane l of segment k as a ratio to time available (hence, Eq. 2 is dimensionless). The workload parameters for a unit of flow (α_z) are all measured in units of time per vehicle. These are functions of the segment length (l) and of the workload for a particular movement (see Hall, 1996, for specifics). In our implementation, flow is measured in vehicles per hour, whereas α_z are measured in seconds per vehicle. Hence, $W_{k/l}(t)$ equals the number of seconds in an hour (3600), and is identical for all segments/lanes/periods. If all parameters are measured in the same time unit, the upper bound on Eq. 2 would be one.

The workload parameters are defined by the following functions:

$$\alpha_1 = c_{str} \quad (\text{continuing straight in a lane in a segment})$$

$$\alpha_2 = c_{in}/l + c_{str}/2 \quad (\text{entering a lane in a segment})$$

$$\alpha_3 = c_{out}/l + c_{str}/2 \quad (\text{exiting from a lane in a segment})$$

$$\alpha_4 = c_{in}/l + c_{out}/l \quad (\text{passing through a lane in a segment})$$

where c_{str} is the workload for continuing straight in a lane (seconds), c_{in} is the workload for entering a lane (meter-seconds), and c_{out} is the workload for exiting a lane (meter-seconds). The formulation assumes that lane changes occur at random within segments, and that traffic passing through a lane only resides in the intermediate lane momentarily. Therefore, one half of c_{str} is allocated to the entering lane and the other half is allocated to the exiting lane (hence, each vehicle exerts a minimum workload of c_{str} in each segment).

The flows $f_{k/lz}(t)$ are derived from the path flows in a manner that accounts for non-integer travel times. Let:

τ_{ik} = travel time from origin i to the start of segment k (measured in time periods), assumed to be path independent
 $S_{k/lz}$ = set of paths that use lane l of segment k with flow type z

The flows $f_{k/lz}(t)$ are defined by the flows on paths in the set $S_{k/lz}$. Using the symbol $[]^+$ to denote the next largest integer than the enclosed quantity and $[]^-$ to represent the next smallest integer:

$$f_{k/lz}(t) = \sum_{S_{k/lz}} F_{ijk}(t - [\tau_{ik}])([\tau_{ik}]^+ - \tau_{ik}) + \sum_{S_{k/lz}} F_{ijk}(t - [\tau_{ik}]^+)(\tau_{ik} - [\tau_{ik}]^-) \quad (3)$$

With non-integer travel time, Eq. 3 allocates flow to periods on a proportional basis. If, for instance, $\tau_{ik} = 3.6$ periods, then 60% of the flow that originates in period $t-4$ is allocated to $f_{k/lz}(t)$ and 40% of the flow that originates in period $t-3$ is allocated to $f_{k/lz}(t)$.

In addition to lane/segment workload constraints, ramps are limited in how much flow they can accommodate, or by a pre-selected metering rate:

$$f_i(t) \leq c_i(t) \quad (4a)$$

$$f_j(t) \leq c_j(t) \quad (4b)$$

where $f_i(t)$ and $f_j(t)$, respectively, represent the flow entering an on-ramp i or exiting an off-ramp j in period t .

3.2 Objective Functions and Origin/Destination Patterns

The objective is to maximize the total flow, where the total flow is defined as the sum of the flows from each origin to each destination (across all paths and periods):

$$\max \sum_{i,j,k,t} F_{ijk}(t) \quad (5)$$

The formulation assumes a fixed origin/destination pattern, which is defined on a proportional basis:

$$\sum_k F_{ijk}(t) = \left[\sum_{i,j,k,t} F_{ijk}(t) \right] p_{ij}(t) \quad (6)$$

where:

$p_{ij}(t)$ = proportion of total flow (summed across all periods and paths) that travels from origin i to destination j in period t .

$$\sum_{i,j,t} p_{ij}(t) = 1$$

$p_{ij}(t)$ are input parameters, which depend on vehicle origin/destination patterns for the highway under investigation. The underlying philosophy is that the linear-program

determines the maximum highway capacity, under the condition that no origin/destination pair is preferred over any other. Hence, the formulation does not allow the proportions to be violated, even when some lane/segments have surplus capacity.

3.3 Solution by Column Generation

The LP was solved using the CPLEX Linear Programming Solver (CPLEX 4.0, 1996) through use of a column generation procedure, outlined below. The procedure is initialized by solving a static formulation of the lane assignment problem. This entails summing $p_{ij}(t)$ across time periods and solving the resulting time-independent linear program:

- 1) Solve lane assignment problem as a static problem using Hall and Lotspeich (1996).
- 2) Identify paths used in solution to static problem. Add these paths to the set P , the set of usable paths.
- 3) Heuristically generate additional paths, and add these paths to the set P .
- 4) Solve dynamic L.P. based on the path set P .
- 5) Using dual variables for lane/segment/time capacity constraints to derive arc costs, solve for shortest paths between all origin/destination pairs in each time period
- 6) Based on solutions to (4) and (5), determine whether solution to dynamic L.P. is within acceptable bound of its optimum. If yes, stop. If no, add all shortest paths identified in step (5) to the set P , and return to step (4).

Step (3) is intended to reduce the number of iterations in steps 4-6 by quickly producing reasonable supplemental paths. This was accomplished through a pre-specified

assignment pattern that generated one path for each origin/destination pair. Each pair was assigned to a single lane, representing the left-most lane that vehicles would utilize on their trip. The procedure required that trips assigned to any given lane must be strictly longer than all trips assigned to any lane to its right. Hence, the shortest trips are assigned to the right-lane and the longest trips are assigned to the left-lane. The user selects non-overlapping ranges for the trip lengths assigned to each lane. The heuristic also assumes that vehicles move left or right by no more than one lane within any segment, with left lane changes only occurring in off-ramp segments, and right lane changes only occurring in neither segments (refer to Figure 1). Experimentation with static formulations revealed that other types of lane changes are rarely optimal (Hall and Lotspeich, 1996).

The L.P. in step (4) was solved using the CPLEX 4.0 optimizer, as were the shortest path problems in step (5), which were modeled as trans-shipment problems. The shortest path formulation used dual variables for the constraints in Eq. 2 to derive arc costs. Let:

$\beta_{kl}(t)$ = dual variable for lane l of segment k in period t

$\gamma_{kld}(t)$ = cost for arc in segment k , beginning in lane l and ending in lane d , for period t

The arc cost for a "straight" arc (not involving lane change) is easily derived:

$$\gamma_{kld}(t) = \alpha_1 \beta_{kl}(t), \quad d = l \quad (7)$$

Equations are more complicated for arcs involving lane changes. These were computed according to the dual variable for each lane/segment/period used by an arc, multiplying the dual variable by the flow workload:

$$\gamma_{kld}(t) = \alpha_3 \beta_{k/}(t) + \alpha_2 \beta_{kd}(t) + \alpha_4 \sum_{s=l+1}^{d-1} \beta_{ks}(t) \quad d \geq l+2 \quad (8a)$$

$$\gamma_{kld}(t) = \alpha_3 \beta_{k/}(t) + \alpha_2 \beta_{kd}(t) \quad d = l+1, l-1 \quad (8b)$$

$$\gamma_{kld}(t) = \alpha_3 \beta_{k/}(t) + \alpha_2 \beta_{kd}(t) + \alpha_4 \sum_{s=d+1}^{l-1} \beta_{ks}(t) \quad d \leq l-2 \quad (8c)$$

The shortest path is solved dynamically, accounting for non-integer travel times. Hence, for a given origin ramp and departure period, the arc cost is further modified, to account for the proportion of flow occurring within each time period:

$$\begin{aligned}
\omega_{k/d}(i,t) &= \text{cost for arc in segment } k, \text{ beginning in lane } l \text{ and} \\
&\quad \text{ending in lane } d, \text{ for period } t, \text{ for trips originating at } i \text{ in period } t \\
&= \gamma_{k/d}(t+[\tau_{ik}])([\tau_{ik}]^+ - \tau_{ik}) + \gamma_{k/d}(t+[\tau_{ik}]^+)(\tau_{ik} - [\tau_{ik}]) \quad (9)
\end{aligned}$$

$\omega_{k/d}(i,t)$ is the arc cost that is used in solving the shortest path problems.

The solution to step (6) can be used to check whether the solution to the dynamic L.P. (step 3) is within an acceptable bound of the optimum. Let:

$$\begin{aligned}
c_{ij}(t) &= \text{length of shortest path between origin } i \text{ and destination } j, \text{ for} \\
&\quad \text{departure in period } t \\
c'_{ij}(t) &= \text{length of shortest path between origin } i \text{ and destination } j, \text{ for} \\
&\quad \text{departure in period } t, \text{ restricted to the current set of paths} \\
&\quad \text{used in the dynamic linear program.} \\
C_2 &= \sum_{i,j,t} c_{ij}(t) \\
C_1 &= \sum_{i,j,t} c'_{ij}(t) \\
\varepsilon &= \text{maximum acceptable error (as a proportion)}
\end{aligned}$$

In an optimal solution C_2 is identical to C_1 , indicating that total flow cannot be marginally increased by reassigning flow from the set of used paths to an alternative path identified in the dual-based shortest path problem. In our implementation, the program is terminated when:

$$[C_1 - C_2] / C_1 \leq \varepsilon \quad (10)$$

Where ε is set to be a very small value (.01 or smaller).

4. COMPUTATIONAL EXPERIMENTS

Experiments measured how total flow and computation time are affected by the following model features:

- Number of lanes (2 or 4)
- Time of day variations in demand (constant, random or triangular patterns)
- Length of highway (16, 48, 64 or 80 segments).
- Lane change workload ($c_{in} = c_{out} = 100, 500$ or 1000 meter-seconds)

In all experiments, the workload parameter for staying in a lane was set at $.5$ s. The segment length is assumed to be 1000 meters in all cases. Therefore, the workload values translate into the following model coefficients:

$$\alpha_1 = .5 \text{ s (all cases)}$$

$$\alpha_2 = .35, .75 \text{ or } 1.25 \text{ s}$$

$$\alpha_3 = .35, .75 \text{ or } 1.25 \text{ s}$$

$$\alpha_4 = .2, 1, \text{ or } 2 \text{ s}$$

With $\alpha_1 = .5$ seconds, the maximum achievable capacity is $7,200$ vehicles per lane per hour. Lane changing reduces the achievable capacity, as $\alpha_2 + \alpha_3 > \alpha_1$.

Also in all experiments, trip length followed a geometric distribution, with a mean trip length of 16 segments. If the trip length placed the off-ramp beyond the end of the modeled highway, the trip was assigned to the "super-sink" destination. In the

experiments, the highway began with zero traffic, but ended with an amount of traffic equaling the residual off-ramp flow.

In all experiments, highway structure exhibited the same pattern as Figure 1. As shown, the highway is divided into 4-segment blocks, with the pattern: on-ramp, neither, neither (adding a lane), and off-ramp (dropping a lane). Hence, the number of on-ramps equals the number of off-ramps, which are both 1/4 the number of segments.

Time of day patterns were created as follows:

$$p_{ij}(t) = \rho_{ij}v(t) \quad (11)$$

where:

ρ_{ij} = proportion of total flow that travels from origin i to destination j

$$\sum_{i,j} \rho_{ij} = 1$$

$v(t)$ = proportion of total flow that travels in period t

$$\sum_t v(t) = 1$$

In one set of experiments, $v(t)$ was held constant. In another set of experiments, $v(t)$ followed a triangular distribution. In a final set of experiments, $p_{ij}(t)$ was randomly generated, by first a uniform random variable over $[0,100]$ and then normalizing the result by dividing each variable by the sum of the random variables. The randomized demand pattern assumed that all flow originated at on-ramps and all flow was destined for off-ramps (i.e., the highway begins and ends with zero flow).

4.1 Total Network Flow

As shown in Table 1, network flows exhibit patterns that are quite similar to static results. For example, for the triangular demand pattern with 12 time periods, the following were observed:

- Increased lane-change workload causes total flow to decline.
- The lane-change workload affects total flow the most on short highways (due to relatively more lane-changing), and on highways with many lanes (due to the number of lane changes required to reach left-most lanes).
- Increasing the number of lanes does not always increase capacity, especially when the highway is short and the lane-change workload is large.
- Increasing the highway length always increases total flow, with the greatest effect when the lane change coefficient is large.

4.2 Computation Time

Table 2 provides computation time results, showing total CPU time covering all phases of the algorithm (including solving the static problem and all iterations of the column generation procedure). The algorithm is non-deterministic, and computation time can vary substantially among problems of the same size. However, in most cases, when the number of segments is 48 or smaller and the number of periods was 12 or smaller, the problem could be solved in under 2000 seconds (usually, much less than 2800 seconds). Problems of this size have 792 origin/destination/time period pairs, each of which has as many as 4^{48} feasible routes. The randomly generated problems had the fastest solution time. One problem with 80 segments, 4 lanes and 12 periods was solved in 4751 seconds.

Surprisingly, problems with constant demand tended to be hardest to solve. This is largely due to end effects. Even with constant demand entering the network, traffic in the initial and final time periods is non-stationary. We speculate that the constant

Table 1. Total Network Flow

Triangular Demand Pattern: 12 Time Periods

Lane-Change Parameter

Segments	Lanes	100	500	1000
16	2	134	114	81
48	2	237	219	189
64	2	294	274	240
80	2	355	335	296
16	4	202	134	81
48	4	474	403	242
64	4	589	*	323
80	4	710	*	*

Table 2. Computation- Time and Iterations

Constant Demand over Time

Segments	Lanes	Periods	Iterations	Total Time
16	2	4	3	7
16	2	12	2	16
16	4	4	1	8
16	4	12	3	57
48	2	4	1	81
48	2	12	1	282
48	4	4	9	1870
48	4	12	*	*
64	2	4	2	292
64	2	12	1	643
64	4	4	19	8848
64	4	12	*	*
80	4	4	*	*
80	4	12	*	*

Triangular Demand over Time

Segments	Lanes	Periods	Iterations	Total Time
16	2	4	1	4
16	2	12	3	17
16	4	4	1	7
16	4	12	2	23
48	2	4	4	155
48	2	12	1	129
48	4	4	4	448
48	4	12	5	7602
64	2	4	3	384
64	2	12	1	488
64	4	4	5	1428
64	4	12	*	*
80	4	4	5	3011
80	4	12	*	*

* Not solvable

Table 2. (continued) Random Demand Pattern

Segments	Lanes	Periods	Iterations	Total Time
16	2	4	1	4
16	2	12	1	6
16	4	4	1	5
16	4	12	1	10
48	2	4	1	66
48	2	12	1	217
48	4	4	1	283
48	4	12	1	402
64	2	4	1	861
64	2	12	1	1183
64	4	4	1	808
64	4	12	1	1450
80	4	4	3	1364
80	4	12	1	4751

demand patterns are harder to solve than the triangular problems because the residual traffic is more significant. Also, we speculate that the randomized problems are easier to solve because none of the traffic was destined for the "super-sink", for which it is more difficult to generate optimal paths.

In all problems, we speculate that computation time might be somewhat larger than it would otherwise be due to the highly degenerate nature of the static problem. As discussed in Hall and Lotspeich, the problem is characterized by multiple-global-optima, as various paths can yield equivalent total network flow. It may be that the dynamic formulation must rely on a greater number of these paths than the static formulation, which require many column generation iterations to identify.

5. HOLLYWOOD FREEWAY CASE STUDY

The Hollywood Freeway is an extremely congested roadway, stretching from Downtown Los Angeles to the Hollywood District. The road is about 50 years old, making it one of the oldest freeways in the state. As was characteristic of that period, it has closely spaced on and off ramps (a little more than 1/2 mile between interchanges). Many of these are very short by today's standards, and many contain tight radius curves.

Our study section is from Vignes Way to Highland Way, covering the urbanized portion of the freeway. The number of lanes in this section is either 3 or 4 per direction, and average daily traffic flow varies from about 220,000 vehicles per day to 260,000 vehicles per day (both directions). The combination of high traffic volume and frequent weaving sections make this one of the most congested highways in the LA region.

The highway was modeled in 55 segments with LANE-OPT, a static lane optimization program. Due to the frequent entrances and exits, some of these segments were quite short -- as small as 80 m. A synthetic origin-destination matrix was created from measured daily traffic flows, and the program was formulated to maximize total throughput. Workload parameters were set as follows:

$$c_{str} = .5 \text{ s (7200 vehicles/hour)}$$

$$c_{in} = c_{out} = 100 \text{ m-s, 500 m-s or 1000 m-s}$$

The larger values of $c_{in} = c_{out}$ represent higher workloads for lane-changes.

The simulation results are summarized below in Table 3.

Table 3. Case Study Results

$c_{in} = c_{out}$	Total Highway Throughput	Maximum Throughput (all lanes)	Maximum Throughput per Lane
100 m-s	28,700 veh/hr	18,400 veh/hr	4,600 veh/hr
500 m-s	7,600 veh/hr	4,900 veh/hr	1,200 veh/hr
1000 m-s	4,000 veh/hr	2,540 veh/hr	635 veh/hr

These capacity values are considerably less (50% or more) than the cases in Hall and Lotspeich (1996). For the 500 and 1000 m-s examples, the capacity is even less than that of a manual highway. Through analysis of linear program constraints, we found that the highway capacity is not limited by the number of lanes, as the left-most lane never reaches capacity. Instead highway capacity is limited by the ability of the right-hand lane to absorb on and off traffic, especially in the vicinity of the I-110, Glendale Boulevard and Highland Avenue interchanges, all of which generate considerable traffic. These points are consistent with where congestion occurs today on the roadway.

It is safe to conclude that the combination of frequent exits and entrances, short trip lengths, and high lane-change workload is not conducive to highway automation. To make an automated highway work in this highly urbanized freeway, the system would

have to be designed to allow for short-headway lane changes or it would have to be designed to accommodate only longer trips, with manual lanes available to serve short distance trips. A partial solution would be to eliminate some of the more closely spaced ramps, thus reducing some of the worst weaving sections.

6. CONCLUSIONS

This research has developed and tested two linear programming models, one static and the other dynamic, for assigning traffic to lanes on an automated highway, and for evaluating highway capacity. The focus of this paper has been on the dynamic model. The static model has been reported elsewhere.

The formulation in this paper assumes a fixed origin-destination pattern (expressed on a proportional basis) and a workload based capacity formulation. The origin-destination pattern is allowed to vary among time periods. The problem is solved with a path-based formulation and a column generation procedure.

In our computational tests, problems with up to 48 segments, 4 lanes and 12 time periods were consistently solved with the algorithm. Because the algorithm is non-deterministic, computation time varies for problems of the same size. Larger problems can only be solved in some instances. Qualitatively, solutions behave similarly to static formulations of the lane assignment problem. Increased lane-change workload causes total flow to decline, especially on short highways and highways with many lanes. Also, increasing the number of lanes does not always increase capacity, especially when the highway is short and the lane-change coefficient is large. Finally, increasing the highway

length always increases capacity, with the greatest effect when the lane change coefficient is large.

Our analysis of the Hollywood Freeway illustrated the problems of frequent on and off ramps coupled with short trips that an AHS would confront in an urbanized environment. In this application, the lane-change workload would have to be reasonably small to generate substantial capacity gains over a conventional highway. However, if a lane-change can be achieved in 100 m-s (e.g., 20 m additional space over 5 seconds), then capacity could reasonably be more than double that of a conventional highway.

Through future research, it may be possible to develop heuristics that are more effective at identifying the optimal path set. This could reduce the number of column generation iterations and the computation time per iteration, making the procedure even more efficient.

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