A Design of Lane & Segments on Highway Automation System: A Review

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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.

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 spacing's 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 and through the use of a linear programming model for a static network. 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. 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.

Review of Literature:

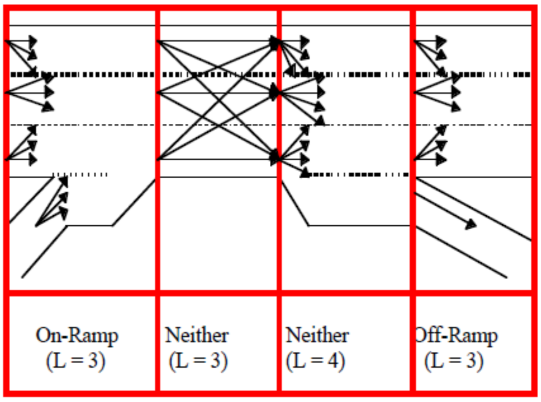
The earliest systematic study of automated highway capacity appears to be the paper by Rumsey and Powner, which examined a moving cell operating concept. Recently, however, the interest in automated highways has focused more on the platooning concept, as introduced by Shladover. Shladover developed capacity estimates based on a variety of safety criteria, in which the objective was to prevent severe collisions. In a related paper, 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. Smart Path 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. 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. It developed a stochastic queuing 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 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 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 which activity plans (covering velocity and assignment of maneuvers) were developed for a single lane highway. Subsequent research has lead to the creation of the "SMARTCAP" simulator.

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.

Network Representation:

As shown in Figure 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 outgoing 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).



Highway Segments

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, 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.

Network Flow:

As shown in Table1, 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.

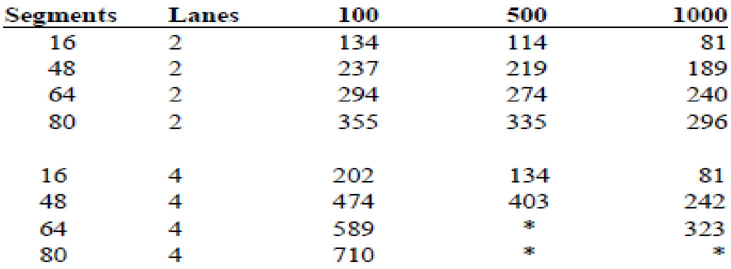
- The lane change workload affects total flow the most on short highways (due to relatively more lane changing), and on highways with many lanes (due to the number of lane changes required to reach left most lanes).
- Increasing the number of lanes does not always increase capacity, especially when the 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.

Computation Time:

As shown in 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 less than 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

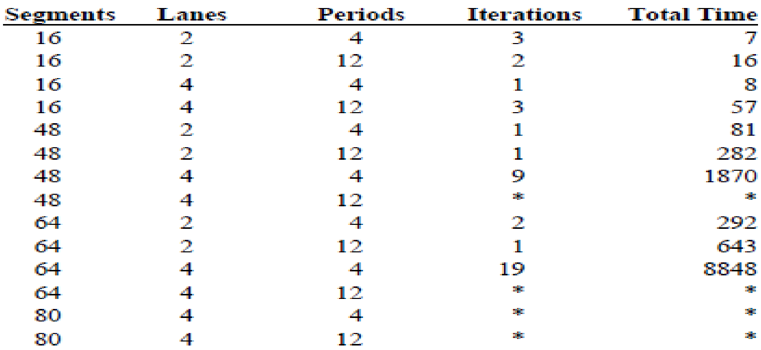
Triangular Demand Pattern: 12 Time Periods (Lane Change Parameter)



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	*	*

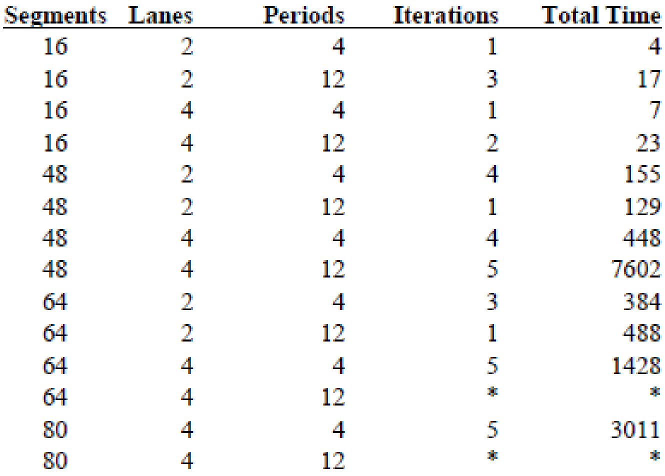
Table 2: Computation Time and Iterations

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	*	*

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 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 requires many column generation iterations to identify.

Conclusion:

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 ms (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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