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DYN-OPT Users Manual

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ABSTRACT

DYN-OPT is a linear program that optimally and dynamically assigns traffic to lanes on an automated highway. The program maximizes the total flow across the highway over a pre-specified length of time. DYN-OPT solves a path-based formulation in which the highway is represented by discrete segments, time is divided into periods and traffic between origins and destinations follows a user-specified distribution. The model assumes that each lane/segment has a fixed capacity that can be allocated among four types of movement: (1) straight, (2) lane changes into a lane, (3) lane changes out from a lane, (4) lane changes that pass through a lane. Paths are defined as sequences of these movements. Flow originating from an origin during a period travels through the highway along a path and exerts a workload on each lane/segment/period traversed. The program uses a column generation strategy, where columns are generated by solving shortest path problems.

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

EXECUTIVE SUMMARY

DYN-OPT is a linear program based software package that optimally and dynamically assigns traffic to lanes on an automated highway. The program maximizes the total flow across the highway over a pre-specified length of time. DYN-OPT solves a path-based formulation in which the highway is represented by discrete segments, time is divided into periods and traffic between origins and destinations follows a user-specified distribution. The model assumes that each lane/segment has a fixed capacity that can be allocated among four types of movement: (1) straight, (2) lane changes into a lane, (3) lane changes out from a lane, (4) lane changes that pass through a lane. Paths are defined as sequences of these movements. Flow originating from an origin during a period travels through the highway along a path and exerts a workload on each lane/segment/period traversed. The program uses a column generation strategy, where columns are generated by solving shortest path problems.

DYN-OPT is based on the same modeling concepts as LANE-OPT, which was developed in early 1996. However, LANE-OPT is a static formulation (i.e., flows are assumed to be constant over time), whereas DYN-OPT is a dynamic formulation (i.e., flows vary across time periods). DYN-OPT provides flexibility to model time-varying demand. However, computational and data requirements are greater. Either model can be used to analyze the effect of lane change penalty parameters on highway capacity. LANE-OPT is recommended for evaluation of automation concepts, whereas DYN-OPT is recommended for future evaluation of implementations at specific sites.

The software was written in C, and uses the CPLEX Callable Library version 4.0 [1], which is available from CPLEX Optimization, Inc. CPLEX Callable Library is used to perform column generation iterations through library routines automatically. CPLEX Callable Library is available for IBM compatible machines and many UNIX systems. Since the CPLEX Callable Library binaries differ among operating systems, DYN-OPT must be compiled and linked with an appropriate CPLEX binary file. The user must be licensed to the CPLEX Callable Library version 4.0.

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1. INTRODUCTION

DYN-OPT is a linear program that optimally and dynamically assigns traffic to lanes on an automated highway. The highway is represented by discrete segments of user-specified lengths and is of finite length. Similarly, time is discretized and measured in periods. The program is based on a path-oriented linear programming (LP) formulation. It maximizes the total flow across all origin-destination pairs, and across all time periods. Each path comprises a sequence of four types of movement: (1) straight, (2) lane changes into a lane, (3) lane changes out from a lane and (4) lane changes that pass through a lane. Each of these movements exerts a workload on segment of a lane in a specific period. Flow originating from an origin during a period travels through the highway along a path and exerts a workload on each lane/segment/period traversed.

DYN-OPT creates an initial set of "good" paths, solves an initial LP restricted to those paths, generates additional paths from a shortest path formulation using dual prices, then re-optimizes the LP. This column generation procedure continues until a duality gap in the shortest path problem falls below a pre-specified percentage.

The highway is modeled as a series of segments indexed by location, type (on-ramp, off-ramp, neither), number of lanes, ramp capacity and travel time. On-ramp nodes are source nodes without entering arcs, and off-ramp nodes are sink nodes without out-going arcs. Source nodes are also placed at the start of each lane in the first segment, and a super-sink nodes 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 nodes allows the assignment of continuing traffic to be optimized among lanes.

The formulation accounts for non-integer travel times by proportionately allocating flow among periods. For example, if the travel time from an origin to a segment is 2.6 time periods, then 40 percent of the traffic that that enters the network in period one will travel through the segment in period 3 and 60% will travel through the segment in period 4.

Origin-destination patterns are expressed proportionately. That is, the user must enter data representing:

P_{ijt} = proportion of total traffic that travels from origin i to destination j in period t.

where

$$\sum_{ijt} P_{ijt} = 1$$

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All of the experiments were performed on a SUN SPARC server 1000 with 256 MB of RAM. Experiments were conducted for highways with up to 80 segments, 4 lanes and 12 periods.

2. SYSTEM STRUCTURE

DYN-OPT takes four input files and generates an output file that not only includes the detailed solution but also a log file that reports the status of the problem at each column generation iteration (Figure 1). The input files are a highway description file, origin-destination file, user-specified lane assignment file and parameter file. The user specifies an output file and all solution information is written on that file. The solution is found in four phases:

1) In the first phase, DYN-OPT reads all four data files, and creates another data file for a static version of the dynamic problem. It simply sums the flow fractions of all periods into one period (i.e., creates an origin-destination file for the static version of the problem). Then it creates and solves the static problem using LANE-OPT [2].

2) In the second phase, DYN-OPT translates the output of LANE-OPT into a form that is usable for a path-based formulation. LANE-OPT models the static lane assignment problem as a multi-commodity flow network, where destinations represent commodities. Thus, it gives optimal arc flows rather than paths. DYN-OPT decomposes this static solution into paths, using a path decomposition algorithm. These paths are put into the initial path set.

3) In the third phase, DYN-OPT heuristically creates additional paths. As identified by Hall and Lotspeich [3], optimal lane changes to the left usually occur in ‘off-ramp’ segments and similarly lane changes to the right occur in ‘neither’ segments. Furthermore, longer trips tend to use lanes to the left of shorter trips, and most trips only use one lane for most of their trip. The lane-assignment file asks the user to specify a preferred lane for each trip according to length. DYN-OPT takes this as input and generates paths following the rules explained above.

4) In the fourth phase, DYN-OPT constructs the path-based LP from the set of initial paths and solves the LP. Dual variables, which correspond to the workload constraints,

are used to determine whether other paths exist that can increase the total flow of the highway. These paths are determined by solving shortest path problems based on the costs from dual prices for capacity constraints (representing a segments/lanes/periods). A

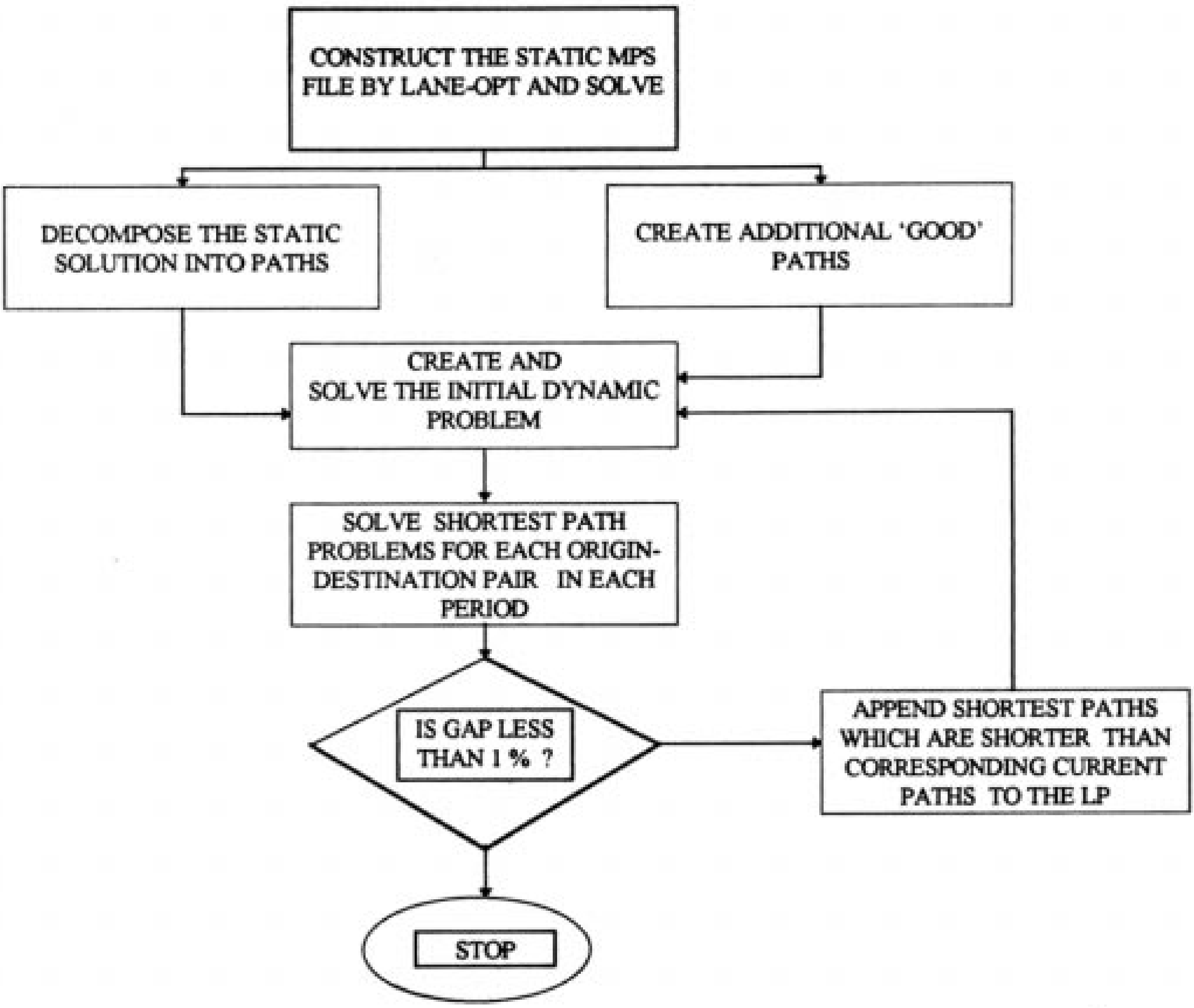

Figure 1. Program Structure

shortest path is found for each origin/destination pair and each period. If the difference between the total length of the shortest paths among the current paths and the total length of the shortest paths among all paths is greater than 1%, the shortest paths are added to the path set and the LP is resolved. The procedure repeats until the gap falls below 1%. Finally, DYN-OPT writes information about optimal flows and paths to the output file.

3. INPUT FILES

DYN-OPT uses four input files: (1) highway description file, (2) origin-destination file, (3) parameter file and (4) user-specified lane assignment file, as described in this section.

3.1. Highway description file

The highway description file includes all required information for the highway model. It defines the highway as a series of discrete segments with five attributes: type (entry ramp, exit ramp, or neither), length, number of manual lanes, number of automated lanes, and ramp-flow capacity (ramp segment). Segment type is defined as follows: 0 for an on-ramp, 1 for an off-ramp, 2 and 3 for a no-ramp segment, where 3 adds a lane. This file also includes the travel times between segments measured in time periods. Each row of the highway description file specifies a segment, and each column represents an attribute of that segment:

Column 1: Index
Column 2: Type
Column 3: Length (in meters)
Column 4: Number of manual lanes
Column 5: Number of automated lanes
Column 6: Ramp-flow capacity (vehicles per hour); if not a ramp segment, enter the number 1.
Column 7: Travel time to traverse segment, measured in time periods.

3.2. Origin-Destination File

This file represents the distribution of trips among origin/destination pairs and periods. Each row of the file gives the proportion of total flow originating from an origin to all other destinations for a specific period. The first line of the origin-destination file consists of three integers representing number of periods, number of on/off-ramps (the number of on-ramps and off-ramps must be the same), and number of initial lanes of the highway, in this order. Let the number of periods be T, number of on/off-ramps be N, and number of initial lanes be L. Then, the rows of the origin-destination file will be organized as follows.

Row 1: T N L

Next L*T rows:

Rightmost lane

P_{111} P_{121} P_{131} ……. P_{1N1} $P_{1\ END\ 1}$

.

.

P_{11T} P_{12T} P_{13T} ……. P_{1NT} $P_{1\ END\ T}$

.

.

.

.

Leftmost lane

P_{L11} P_{L21} P_{L31} ……. P_{LN1} $P_{L\ END\ 1}$

.

.

P_{L1T} P_{L2T} P_{L3T} ……. P_{LNT} $P_{L\ END\ T}$

These L*T rows correspond to the flows originating from the initial lanes of the highway. P_{ijt} represents the proportion of total flow that originates in the i'th initial lane and is destined for the j'th destination lane in period t. END represents the destination for the flows that do not exit the highway. Since all of the destinations are after the first segment, all of the above rows have N+1 entries.

Next N*T rows:

First on-ramp

P_{111} P_{121} P_{131} ……. P_{1N1} $P_{1\ END\ 1}$

.

.

P_{11T} P_{12T} P_{13T} ……. P_{1NT} $P_{1\ END\ T}$

.

.

.

j'th on-ramp

$P_{j\ j\ 1}$ $P_{j\ \ j+1\ 1}$ $P_{j\ \ j+2\ \ 1}$ ……. $P_{j\ N\ 1}$ $P_{j\ END\ 1}$

.

.

$P_{j\ j\ T}$ $P_{j\ j+1\ \ T}$ $P_{j\ j+2\ \ T}$ ……. $P_{j\ N\ T}$ $P_{j\ END\ T}$

.

.

.

Last on-ramp

$P_{N\ END\ 1}$

.

.

$P_{N\ END\ T}$

These N*T rows correspond to the flows originating from the on-ramps of the highway. P_{ijt} represents the flow originating from the i'th on-ramp and destined to the j'th destination in period t.

3.3. Parameter file

This file has only one row and includes the parameters of the problem. The entries are: workload coefficients of staying in the same automated lane through a segment, of moving into an automated lane, of moving out of an automated lane, of staying in the same manual lane, of moving into a manual lane and of moving out of a manual lane, in this stated order. Workload coefficients for entering and exiting a lane are measured in meter-seconds, whereas the workload coefficient for continuing straight within a lane is measured in seconds.

3.4. User specified lane assignment file

This file includes the information about how additional paths will be generated heuristically. The user must specify lanes for different trip lengths and DYN-OPT will create additional paths by using those lanes and making lane changes as explained in Section 2. This file has two columns as follows.

Length	Lane	
L_1	1	$0 \leq X \leq L_1$
L_2	2	$L_1 < X \leq L_2$
.	.	.
.	.	.
.	.	.
L_{n-1}	n-1	$L_{n-2} < X \leq L_{n-1}$
L_n	n	$L_{n-1} < X \leq L_n$

X represents the trip length above. For this example, in order to create additional paths heuristically, trips of length 0 to L_1 are assigned to lane 1, L_1 to L_2 are assigned to lane 2, ... , and L_{n-1} to L_n are assigned to lane n. If X is greater than L_n, DYN-OPT will assign it to lane n. Lane changes to the left will take place in off-ramp segments and lane changes to the right in neither segments. If there are not enough off-ramp and neither segments within a given trip length, the program will not create a heuristic path.

4. Example Problem

In this section, we solve a small example problem. The data files are as follows.

Highway description file (Filename: hd8_2)

1 0 1000 0 2 7200 0
2 2 1000 0 2 7200 0.11
3 3 1000 0 2 7200 0.11
4 1 1000 0 3 7200 0.11
5 0 1000 0 2 7200 0.11
6 2 1000 0 2 7200 0.11
7 3 1000 0 2 7200 0.11
8 1 1000 0 3 7200 0.11

This highway has eight segments, each of which has a length of 1000 meters. It has two on-ramp and two off-ramp segments, with a common ramp-flow capacity of 7200 vehicles/hour. The travel time between adjacent segments is 0.11 periods, and the highway begins and ends with two lanes.

Origin-Destination file (Filename: od8_2_4)

4 2 2
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.015625 0.011719 0.055990
0.031250 0.023438 0.111979
0.031250 0.023438 0.111979
0.015625 0.011719 0.055990
0.015625 0.067708
0.031250 0.135417
0.031250 0.135417
0.015625 0.067708

We consider four periods in this example. The highway begins with zero flow in all periods. The flow pattern is 'geometric' in trip length, and triangular in time. This means marginal probability mass function of trips in terms of trip length is geometrically distributed (with a mean trip length of 16 segments in this example) and similarly, marginal probability mass function over time is discrete triangular (with a median time of

(T+1)/2 periods, or 2.5 periods in this example). Thus, the flow proportion for trip length x (x is measured in four-segment blocks) in period t, P_{xt}, is calculated as follows.

$$P_{xt} = f(t) * (0.25)(0.75)^x$$

where $k = [T/2]^-$ and

$$f(t) = \begin{cases} t / (k*(k+1)) , & 1 \le t \le k \\ (T-t+1) / (k*(k+1)) , & t > k \end{cases}$$

Parameter file (Filename: param1)

0.5 500 500 0.5 500 500

In this example, the workload coefficient of moving straight along a lane is 0.5 seconds, and workload coefficients of both moving in and out from a lane are 500 meter-seconds. All parameters are the same for both manual and automated lanes.

User-specified lane assignment file (Filename: add)

4000 1
8000 2
12000 3
16000 4
20000 5

DYN-OPT creates heuristic paths by using lane 1 for trip lengths between 0 and 4000 meters and lane 2 for trips between 4000 and 8000 meters. Since we have only two lanes and eight segments, DYN-OPT ignores the last three rows of this file in the example.

We run this example program as follows. Italicized entries after a prompt represent user responses.

prompt(1): *dynopt*

*********************DYNOPT*********************

You must type the command in the following form:

dynopt <fname1> <fname2> <fname3> <fname4> <fname5>

WHERE:

fname1 : name of origin/destination file
fname2 : name of highway description file
fname3 : name of user-specified lane assignment file
fname4 : name of parameter file
fname5 : name of output file

EXITING...

DYN-OPT shows the form of the command line if entered incorrectly as above.

prompt(1): *dynopt od8_2_4 hd8_2 add param1 out*

DYN-OPT solves the problem and writes the optimal solution to the file "out". This file can be viewed as follows

prompt(1): *more out*

SOLUTION OF THE STATIC PROBLEM

TOTAL FLOW =   9599.96

CPU Time for static problem: 0.88 sec.

INITIAL SOLUTION FOR THE DYNAMIC PROBLEM

TOTAL FLOW :   28799.94

Solution to SP Problem

UB = 12.0000
LB = 12.0000

GAP (% of UB) = 0.0000 %

THE CURRENT SOLUTION IS WITHIN 0.00 % OF OPTIMUM
NO COLUMN GENERATION ITERATIONS

CPU Time for solving initial dynamic problem: 0.50sec.

Total CPU Time : 1.38 sec.

OPTIMAL FLOW INFORMATION

Origin	Destin.	Period	Path #	Flow
1	4	1	1	450.00
1	4	2	1	900.00
1	4	3	1	900.00
1	4	4	1	450.00
1	8	1	2	337.51
1	8	2	3	675.01
1	8	3	3	675.01
1	8	4	1	337.51
1	10	1	1	1612.51
1	10	2	2	3224.99
1	10	3	1	1838.20
1	10	3	2	1386.79
1	10	4	1	1612.51
5	8	1	1	450.00
5	8	2	1	900.00
5	8	3	1	900.00
5	8	4	1	450.00
5	10	1	1	1949.99
5	10	2	1	3900.00
5	10	3	1	3900.00
5	10	4	1	1949.99

DETAILED PATH INFORMATION

Paths from 1 to 4:

Path 1:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	1	-1

Path 2:

Segment	Beg.lane	End lane	Change
1	0	2	2
2	2	3	0
3	3	1	-2

Paths from 1 to 8:

Path 1:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	2	0
4	2	1	0
5	1	1	0
6	1	2	0
7	2	1	-1

Path 2:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	2	0
4	2	2	1
5	2	2	0
6	2	3	0
7	3	1	-2

Path 3:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	2	0
4	2	2	1
5	2	2	0
6	2	2	-1
7	2	1	-1

Path 4:

Segment	Beg.lane	End lane	Change
1	0	2	2
2	2	3	0
3	3	3	0
4	3	2	0
5	2	2	0
6	2	3	0
7	3	1	-2

Paths from 1 to 10:

Path 1:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	2	0
4	2	2	1
5	2	2	0
6	2	3	0
7	3	2	-1
8	2	2	0

Path 2:

Segment	Beg.lane	End lane	Change
1	0	1	1
2	1	2	0
3	2	2	0
4	2	2	1
5	2	2	0
6	2	3	0
7	3	3	0
8	3	3	0

Path 3:

Segment	Beg.lane	End lane	Change

1	0	1	1
2	1	2	0
3	2	2	0
4	2	1	0
5	1	1	0
6	1	2	0
7	2	2	0
8	2	2	0

Path 4:

Segment	Beg.lane	End lane	Change
1	0	2	2
2	2	3	0
3	3	3	0
4	3	2	0
5	2	2	0
6	2	3	0
7	3	3	0
8	3	3	0

Paths from 5 to 8:

Path 1:

Segment	Beg.lane	End lane	Change
5	0	1	1
6	1	2	0
7	2	1	-1

Path 2:

Segment	Beg.lane	End lane	Change
5	0	2	2
6	2	3	0
7	3	1	-2

Paths from 5 to 10:

Path 1:

Segment	Beg.lane	End lane	Change
5	0	1	1
6	1	2	0
7	2	2	0
8	2	2	0

Path 2:

Segment	Beg.lane	End lane	Change
5	0	2	2
6	2	3	0
7	3	3	0
8	3	3	0

DYN-OPT optimizes this problem in 1.4 seconds, without performing column generation iterations. The initial path set was sufficient for an optimal solution. The optimal solution uses only one of two available paths for origin 1 to destination 4, origin 5 to destination 8, and origin 5 to destination 10. Three of four available paths are used between origin 1 and destination 8, and two of four available paths are used between origin 1 and destination 10. Notice that most of the flow goes to the end of the highway; the mean trip length of 16 segments is twice the length of the highway.

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