Integrating Dynamic Traffic Management Interventions into the HCM Freeway Facility Methodology

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This paper discusses a dynamic framework and methodology to aid in selection and deployment of Active Traffic Management (ATM) strategies on freeway facilities. The dynamic methodology builds on the current freeway facilities methodology contained in the 2010 Highway Capacity Manual.

The framework simulates near real-time operations and provides functionalities similar to those at Traffic Management Centers. Interventions by an “operator” are allowed to take place at the conclusion of each 15 minute analysis period. At each intervention, ATM strategies’ options are made available to be implemented in the next analysis period or beyond.

The framework accounts for two types of users: Administrators and End Users. The Administrator is responsible for creating the base facility and defining the scenario presented to the End User. The End User is responsible for deploying or adjusting the selected ATM strategies at each intervention based on his/her assessment of the current and past operational conditions of the facility. At the end of each complete analysis run, the End User can readily evaluate the effectiveness of the decisions made during the study period based on a host of generated performance measures.

It is envisioned that this tool can be used as a training mechanism for students, planners, and TMC operators to better equip them on the use of ATM and their potential effectiveness to improve freeway operations. The framework also can serve as a springboard to incorporate predictive models of recurring and non-recurring events in future releases, enabling a more pro-active approach to implementing ATM strategies.

Keywords: ATM, ATDM, Freeway Analysis, Dynamic Strategy Selection, FREEVAL
INTRODUCTION AND MOTIVATION

Nowadays the increase in car-ownership all over the world has burdened motorway networks with considerable congestion problems. This congestion not only reduces the quality of life but also increases the likelihood of incidents. Due to ever rising costs and limited right of way in urban areas, it is generally not possible to increase the capacity of existing freeway facilities through new construction or widening. Consequently a number of non-construction strategies, such as ramp metering, incident management, hard shoulder running, dynamic message signing, variable speed limits, and others, are being implemented as an effective means for relieving freeway traffic congestion. These strategies are part of a larger pool of strategies called Active Traffic Management (ATM).

Many if not most tools designed to assess the effectiveness of ATM strategies are still rooted in a planning level paradigm rather than at the operational level of implementation, for example DTALite (1), Dynasmart(2), VISSIM(3,4), Aimsun(5), and CORSIM (6,7). In essence, such tools assume perfect knowledge of all recurring and non-recurring congestion events across the entire assessment time period, and then proceed to evaluate strategies based on that perfect knowledge and the known sequence of events. In reality, operators who manage the freeway system, while typically familiar with the facility recurrent bottleneck locations and the diurnal demand patterns, cannot predict short term demand changes, traffic breakdown times, the onset of a specific weather events, and incident occurrence and attributes a priori. Having a framework that mimics the incremental progression of facility operation, including receiving information at fixed time intervals from a surveillance system and allowing the ability to intervene in midstream to alter the system status, would be very valuable from a couple of perspectives. First, such a framework can serve as a training tool for TMC operators and transportation students alike to test and compare the effectiveness (or lack thereof) of various ATM strategies in a near real world context. Second, the framework can serve as a springboard to incorporate predictive models of recurring and non-recurring events in future releases, enabling a more pro-active approach to implementing ATM strategies.

This paper therefore proposes a framework that is intended to be an operational level macroscopic simulation environment based on the Highway Capacity Manual (HCM) concepts to evaluate the operations on a freeway facility when using ATM strategies. As a primary objective, it seeks to provide functionalities similar to those available in Traffic Management Centers (TMCs). Both the framework and methodology build on the core freeway facilities methodology of the 2010 Highway Capacity Manual (8) and its most recent update.

BACKGROUND

According to the latest Urban Mobility Report, US urban motorists in 2011 traveled an additional 5.5 billion hours and purchased an extra 2.9 billion gallons of fuel as a result of congestion. The economic impact of degraded mobility has been estimated at $21 billion, which is quickly eroding the nation’s economic competitiveness (9). The Federal Highway Administration (10) estimates that about half of all congestion delays are caused by non-recurrent congestion events, including incidents, weather, work zones, demand surges, and inadequate base capacity.

The freeway facilities methodology in the Highway Capacity Manual (HCM) builds on its core segment analysis and is used to analyze “extended lengths of freeway composed of continuously connected basic freeway, weaving, merge, and diverge segments” (8). For the analysis, each study period can fall within a 24-hour time period and is divided into 15 minute analysis periods. The methodology relies on two connected sets of algorithms for its analysis. The first is the under-saturated method, which applies for no congestion conditions, when no segment has traffic demand that exceeds the available capacity of the segment. The second is the oversaturated method, which is invoked when demand exceeds capacity in at least one segment along the facility. The methodology has been extended to incorporate reliability measures through a hybrid scenario generation approach (11) and to add several Active Traffic Management (ATM) methods into the framework.

A vast amount of literature exists on the use of ATM strategies. The methodologies controlling these countermeasures are applicable at both the planning and operational levels. Active traffic demand
management (ATDM) is the dynamic management, control, and influence of travel demand, traffic
demand, and traffic flow of transportation facilities. Through the use of available tools and assets, traffic
flow is managed and traveler behavior is influenced in real-time to achieve operational objectives (12).
ATM can be considered as a component of ATDM that focus on the management of traffic flow and not
on the management of demand.

A number of tools have been used to assess ATM strategies that range from sketch planning tools
to simulation modeling. As an example, the ATDM analysis framework introduced in the 2010 Highway
Capacity Manual generates 30 scenarios of different events (incidents, weather) on a freeway facility
(8,13). It then allows the assessment of ATDM countermeasures to improve system mobility
performance. This framework uses a planning level approach to enable the analyst to deal with the current
situation on the freeway; however it lacks the ability to generate a set of actions to improve the current
system performance measures without any knowledge of future conditions. This is precisely the situation
faced by a TMC operator, where the consequences of a strategy cannot be known without some predictive
ability of future traffic states.

One of the most effective freeway ATM strategies is ramp metering. Ramp metering was
implemented on the Eisenhower expressway in Chicago for the first time in 1963 (14). Ramp meters are
traffic signals at the entrance of freeways and are driven via a control strategy (controller). The ramp
controller determines metering rates so that the mainline density remains below a critical density, and
consequently the breakdown may be prevented. Ramp metering strategies are generally categorized into
two classes: local strategies and system-wide (coordinated) strategies. Local strategies adjust the
metering rate based on existing traffic conditions near an individual ramp and do not consider other ramps
in the system. System-wide strategies are designed to consider the traffic flow at a larger and wider level
and control several ramp meters simultaneously. Each of the local and system-wide strategies can be pre-
timed or traffic responsive. In pre-timed strategies, the metering rate is fixed during pre-defined time slots
which usually contain the peak hour. In traffic responsive algorithms, the metering rate is generated based
on real-time traffic measurements (15,16). Some examples of existing ramp metering strategies are
demand-capacity metering (17), the ALINEA algorithm (18), model predictive controllers (19,20),
bottleneck algorithms (21,22), and fuzzy controllers (23-25).

Another important ATM strategy is hard shoulder running. Hard shoulder running is the
temporary operation of hard shoulders as running lanes for normal traffic during peak periods. The main
objective of using the shoulder is to provide additional capacity when needed without much infrastructure
expansion. Hard shoulder running has been implemented in a number of countries in Europe as well as in
the United States. A number of studies have been conducted and show that it has numerous safety and
mobility benefits (26-42).

Dynamic Message Signing (DMS), also known as Variable Message Signing (VMS), is an ATM
strategy that seeks to ease congestion by diverting some demands on a freeway facility to other routes.
This is done by deploying informational signs at specific locations along a freeway that display messages
concerning congestion conditions downstream on the facility. Messages can relate information about
non-recurrent events, expected travel times, levels of congestion, detour routes, or delays caused by traffic
incidents. For this framework, we are most concerned with DMS deployment in the case of congestion
due to non-recurring events such as weather, incidents, and work zones. Ideally, a portion of oncoming
traffic will make use of the information and take alternative routes to their final destination. This reduces
the demand on a congested section of a facility, allowing any bottleneck to clear more efficiently around
the congestion event. Some studies estimated that diversion percentages due to DMS ranged from 7% to
21% and are highly dependent on the level of congestion (43). Other studies have found that DMS has
little impact on travel time but can reduce overall delay experienced (44). Studies have been conducted in
both Maryland (45) and Virginia (46) that confirm DMS usefulness as an ATM strategy.

METHODOLOGY
In conducting the analysis, the proposed framework accounts for two types of operators: an
Administrator and an End User. The Administrator is responsible for creating the base facility, which is
akin to generating a seed file in HCM parlance, configuring the availability of ATM strategies, and
defining the performance measures and facility information that will be available to the End User during
the intervention phase. In other words, the Administrator knows the entirety of the conditions and
performance on the facility. The End User analyses the facility using the HCM method, and when
appropriate, invokes interventions by deploying any of the available ATM strategies based on an
assessment of current and past freeway performance. This categorization of the two distinct users is
needed to simulate a TMC environment where the TMC operator does not necessarily have any prior
knowledge of the non-recurring events that might appear on the facility any time in the future. The
framework emulates this by having the Administrator fully define what information is available, while the
End User only has access to the intervention simulation portion of the framework.

The Administrator’s first responsibility is to configure the base scenario, specifying both the
facility geometry and demand inputs. Once this has been done, the Administrator can choose to create a
specific “scenario” on top of the base conditions, in order to simulate real world events. A key
component of the framework is the Administrator’s ability to pre-define the scenario presented to the End
User. An internal scenario generation module allows the Administrator to schedule non-recurring events,
such as weather events (rain, snow), incidents (lane or shoulder closure), or schedule work zones (those
will be available to the end user). The framework also provides the ability to stochastically schedule some
events based on a user specified probability of occurrence (e.g. specify probability of precipitation).
Default adjustment factors for capacity and free flow speed have been developed for all 3 types of events
and are provided to the Administrator as starting guidance (47).

The Administrator then passes control of the facility to the End User who only has access to a
selected (by the Administrator) set of facility information and performance measures. Interventions by
the End User are allowed to take place at the conclusion of each 15 minute analysis period. At each
intervention, selected facility performance measures are presented to the End User, and ATM strategy
options are made available for implementation in the next analysis period or beyond. The freeway
performance conditions in the next analysis periods are thus dependent on the selected ATM treatments.
Further, the framework provides immediate feedback on the effectiveness of the strategies employed to
guide further actions by the management system and/or analysts in the next 15 minutes.

An important added value of this framework is that it makes use of the HCM’s oversaturated
methodology for freeway facilities analysis. In the oversaturated methodology, the computational
resolution is increased instantaneously from 15 minutes to 15 second time steps, enabling the freeway
condition to be updated at short time intervals. This allows for much finer implementation of queue
progression and dissipation and improves the analysis of adaptive strategies (e.g. ramp metering) as
updated information and feedback on congestion are available in a near continuous manner.

At the intervention stage, several ATM strategies can be deployed either individually or in
bundles. Ramp metering rates can be entered manually, or automatically computed using dynamic
metering strategies such as ALINEA (18) and Fuzzy Logic (48). Dynamic message signing (DMS) can
be selected to enable traffic diversions. The diversion starts just downstream of the DMS sign location
and continues through all downstream off-ramps up to the last ramp located before an incident bottleneck
location. Incident management strategies can also be employed to enable a reduction in the duration of
incident events. Other strategies made available in the framework include hard shoulder running and
diversion of traffic from general purpose lanes to managed lanes (when present). Additional ATM
strategies can be introduced in the future. Many default values are provided in the framework for ATM
strategy parameters. This gives Administrators a starting point when coding the scenarios, but they are
also always allowed the flexibility to enter locally calibrated parameter values (e.g. capacity of a hard
shoulder, estimated incident diversion rate)
FRAMEWORK OVERVIEW

There are three phases in the framework. The first phase is solely the Administrator’s responsibility and is where the facility configuration, the scenario generation, and the ATM strategy availability take place. From this point on, the framework shifts to the End User in the next two phases. The second phase consists of executing the analysis, and invoking the interventions, where several ATM strategies can be deployed either individually or in bundles. Strategies such as ramp metering, dynamic message signing (DMS), hard shoulder running, and incident management may be available based on the Administrator’s configuration of that facility. The framework enters the third phase upon completion of an ATM analysis run. Here, summary performance measures comparing the “before ATM” and “after ATM” scenarios are presented to the End User. At this point, the End User is presented with two options: the analysis can either be concluded, or if he/she wishes to explore other potential courses of action, the framework returns to the second phase to carry out additional or alternative ATM interventions. Details of each of the three phases follow.

1. **Administrator Scenario Generation and Strategy Configuration**: In this phase, a seed file is supplemented with a scenario that is characterized with certain non-recurring congestion sources. The Administrator specifies the spatial and temporal availability of ATM strategies in addition to configuring the strategy parameters (capacity, demand, or duration effects). Lastly, the Administrator selects which performance measure outputs, facility information, and event information are available to the End User during the intervention phase.

2. **End User Interventions and ATM selection**: In this phase, a menu of available ATM strategies are suggested to the user to select based on the observed performance measures in the current 15 minute analysis period. The user can opt to exercise one or more of the interventions for any duration (must be a discrete number of 15 minute periods per HCM protocols). Interventions can be stopped or extended or new ones can be added at the end of any 15 min period.

3. **Multi-Run and Comparison**: This phase enables the End User to perform ATM strategy interventions any number of additional times, with output comparisons between the base scenario and each successive ATM scenario run available for comparison and learning.

Figure 1 depicts the high level process flow of the proposed framework, showing the three distinct phases of the framework.

This section details the description of each process shown in Figure 1.

1) **Code Base Facility or Seed File**

In this step, the desired facility is coded by the Administrator. The geometric and demand information of the subject facility needs to be fully characterized in this step for all 15 minute analysis periods in the study period. Once the initial inputs have been coded, it may be necessary to calibrate the coded facility at this step. The Administrator will need to verify the reported performance measures of the coded facility and adjust input data as needed until the desired performance matches empirical observations or local knowledge of its operations.
2) Scenario Generation

The Administrator has access to an internal scenario generation module to schedule weather events, incidents, and work zones. All three types of events can be scheduled deterministically, in which case the Administrator is required to provide the time periods in which the event will occur, as well as the location for both incidents and work zones. Weather events can also be generated stochastically based on a probability of occurrence and a specified expected duration. With each event type, its severity can be specified and the Administrator will be provided with default HCM capacity, free flow speed, and demand adjustment factors (46). These values can be replaced with locally calibrated values according to the facility, if desired. The generated events are shown to the Administrator, who can override any attributes related to the events and/or their impacts.

3) ATM Strategy Availability Configuration:

Once the facility parameters and scenario events have been defined, the Administrator selects the ATM strategies that will be made available to the End User. A list of strategies included for use in the framework can be found in Table 1. ATM strategy availability, as well as any relevant strategy parameters, can be fully customized at this step. Examples of this would include determining the segments where Hard Shoulder Running is allowed, as well as determining the capacity of the open shoulder. For ramp metering, the Administrator can specify the ramps at which it is available and can configure the User Specified and Adaptive strategies that can be deployed.
TABLE 1 List of ATM strategies included in the framework

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Shoulder Running</td>
<td>Opens the hard shoulder as an additional lane with a reduced capacity.</td>
</tr>
<tr>
<td>Ramp Metering</td>
<td>User Specified and Adaptive strategies reducing on-ramp demand, which may result in increase in throughput, if breakdown is prevented.</td>
</tr>
<tr>
<td>Dynamic/Variable Message Signing</td>
<td>Traffic demand diverted to off-ramps between DMS location and downstream incident.</td>
</tr>
<tr>
<td>Incident Management</td>
<td>Facility demand diversion of on-ramp demand.</td>
</tr>
<tr>
<td>GP to ML Diversion</td>
<td>Demand diversion from general purpose (GP) lanes to managed lanes (ML). (where available)</td>
</tr>
<tr>
<td>On-ramp Diversion</td>
<td>Administrator specified demand reduction of incoming on-ramp demand.</td>
</tr>
</tbody>
</table>

4) Specify Output Display Options and Facility Event Information

The Administrator may wish to control the type of output information that is made available to the End User, in order to more accurately represent particular real world facility situations. For example, traffic incidents and weather events can be specified to be shown or hidden, and information, such as the weather forecast, can be made available. Additionally, the freeway performance measures available can be tailored to reflect each specific scenario, with outputs ranging from those as simple as speed, occupancy, or volume counts, up to those making up the full slate of HCM performance measures on a segment by segment basis. Further, the Administrator can designate whether these outputs are available for each HCM segment, or if they are only available at a limited number of sensor locations across the facility.

At the end of this step the related processes for the Administrator are completed, and the coded facility with defined weather and incident events are ready to be simulated by the End User.

5) Perform HCM Analysis for Current AP and Show Partial Results

This is the first step for the End User to proceed with the analysis. The framework will perform the HCM freeway facilities methodology for only the current 15 minute analysis period (AP) at the end of which it will report the (available) freeway performance measures. In performing the freeway facilities methodology in the current AP, the limited output is shown to the user. The demonstration of limited results to the user is based on the level of data that a regular TMC operator has access to.

6) Check if the Current AP is the Last AP

This step checks to see whether the analyzed AP is the last AP of the study period. If the current analyzed AP is the last one, then the process flow proceeds to step 8. Otherwise, a menu of ATM strategies is presented to the End User from which the appropriate strategies (if any) are selected for implementation in the next AP in step 7. Of course, at every AP the user may decide to “do nothing,” and will therefore mirror the base scenario generated by the Administrator.

7) Select a Set of ATM Strategies to Be Incorporated in the Next AP

Based on the available performance measures and system outputs, the End User chooses any combination of the available ATM strategies to apply to the next analysis period. Once an appropriate course of action is chosen, the End User then proceeds to the next AP and returns to step 6. It should be noted that from this point on, the performance measures, facility graphic, and other outputs will serve to provide immediate feedback on the effectiveness of the course of action taken thus far and will guide future deployment of ATM strategies.

8) View Run Analysis Summary

In this step, the End User is presented with an analysis summary comparing the “before” and “after” scenarios to gauge the quality of the interventions performed. The summary contains statistics of
various performance measures for the run so that the End User can readily evaluate the effectiveness of the ATM decision made during the study period.

9) Perform Another Analysis Run?

At this stage, the user is questioned whether he wants to re-run the analysis with a new set of strategies or not. The purpose of the proposed framework is to simulate the conditions of a TMC in order to test and train the TCM users. So, until the End User is satisfied with the performance, he/she may choose to execute multiple intervention runs and compare the effects of different courses of action. If the End User chooses to rerun the analysis, then the process flow returns to step 8 for a new run, otherwise it proceeds to step 13.

10) Report Generator

If the user decides to not proceed with another intervention run, this step generates a report to show the performance across all runs of the End User in selecting the ATM strategies.

EXAMPLE AND CASE STUDY

This section presents an example use of the framework. For this purpose, the framework has been implemented as FREEVAL-DSS (for Dynamic Strategy Selection), building on top of the HCM’s existing computation engine for freeway facilities (FREEVAL).

The base facility used in the example has a length of 6 miles and is made up of 11 HCM segments, including two on-ramps, two off-ramps, and one weaving segment. The study period is 2.5 hours (10 analysis periods) from 4:00pm to 6:30pm. The base conditions lead to mild demand-induced congestion along the facility, but demand never exceeds capacity and no breakdowns occur. The scenario created along with these conditions includes two non-recurring events. The first is a weather event, defined as “medium rain” with an expected duration of 1 hour. The event was chosen to be generated stochastically with a defined occurrence probability of 70%. In this case, the occurrence of the event is uncertain from the user perspective. In this instance, the rain event was actually generated, and took place from 5:15pm to 6:15pm (APs 6-9). The second event is an incident causing a one lane closure in a specific segment for 30 minutes between 4:15pm and 4:45pm (APs 2-3).

Next the ATM strategy parameters and availability were configured. Hard shoulder running was defined to be available on this facility only on certain segments, and ramp metering was made available at all on-ramps. DMS sign placement locations were enabled on specific segments, and if invoked, incident management was configured to reduce the duration of all incident severities by 15 minutes.

In the last portion of the Administrator phase, the display options were configured. Sensor style outputs for both the facility graphic and performance measures were chosen with sensor locations specified on a limited number of segments. Figure 2 shows a screenshot of the Administrator choices of available ATM strategies.
FIGURE 2  Example inputs for weather and incident event generation

Figure 3 illustrates the screenshot available to the End User. It shows a graphic of the facility with sensor output color coded by speed or occupancy. Sensors are numbered according to the segment they are on. The graphic also highlights the incident type and location. A summary performance output table for the current analysis period is also indicated, and is characterized by low speeds and high occupancies just upstream of the incident location. The radio buttons on the bottom of the screen provide a description of any live events (in this case, it will report an incident on segment 7). The user is then prompted to either review a previous analysis period, proceed with no action, or invoke one or more ATM strategies in the subsequent time periods.

FIGURE 3  End User information screen at the end of the second analysis period

Three different ATM sets of strategies were carried out in three separate model runs. The goal of each run was to employ a different strategy to deal with the congestion arising during the study period. In each run, the different strategies were applied for one hour (analysis periods 2-5), as soon as congestion was evident. For this small example, this simple course of action was sufficient. It should be noted, however, that the framework allows complete flexibility to adjust which strategies are currently employed.
at any given intervention. Strategies can always be deployed, ended, or extended at each intervention step.

For the first analysis run, the hard shoulder was opened to traffic on segments 5 through 10 as indicated in Figure 3. The second run employed adaptive ALINEA ramp metering for the on-ramps in segments 2 and 6. Lastly, the third run deployed DMS signs in segments 3 and 5 to promote diversion away from the incident location. Figures 4 shows the effects of the strategies on the facility travel time index (TTI), and Figure 5 on the vehicle hours delay (VHD), respectively. In each figure, the left graph shows the effects on the performance measure in every analysis period, and the right graph shows the overall effects on the cumulative distribution of the measure. The base or “before” scenario run is shown as a dotted line, and each strategy produced various levels of effectiveness. For the example shown, the ramp metering strategy was the least effective, and the hard shoulder running was the most effective.

**FIGURE 4** Effect of the three analysis runs on facility travel time index (TTI)

**FIGURE 5** Effect of the three analysis runs on facility vehicle hours delay (VHD)

**SUMMARY AND CONCLUSIONS**

This paper presents a novel framework based on Highway Capacity Manual 2010 that simulates a real time environment and provides functionalities similar to what are available in Traffic Management Centers. The proposed framework consists of a set of methodologies to model ATM strategies and serves as a freeway operations evaluation. The framework builds on the HCM’s existing freeway facilities methodology and modifies it so that the analysis is performed in a step wise manner. These steps allow
for user interventions at which sets of ATM decisions are made based on the current conditions of the facility.

Strategies, such as adaptive ramp metering and hard shoulder running, are modeled in the HCM analysis context for use in the framework. Specifically, the ALINEA and Fuzzy Logic ramp metering algorithms were selected and implemented in the FREEVAL computational engine. For other strategies, the research team conducted a vast literature review and formulated default sets of adjustment factors that can be incorporated directly in the freeway facilities methodology. These defaults can provide guidance for parameters such as the capacity adjustment factors for use of shoulder based on current number of open lanes.

Further, by distinguishing the analysts as Administrators or End Users, we believe the framework can be used effectively as a training tool for TMC operators. The flexibility given to the Administrator in configuring the facility and scenarios, as well as in defining the availability of ATM strategies and facility information, provides ample tools to accurately represent conditions that could arise in the real world. The information available to the End User is limited in terms of the level of uncertainty regarding future events, and also in terms of the amount of performance data that is provided. Lastly, the ability to perform multiple analysis runs allows for a comparison of effectiveness of the different ATM responses on travel time and delay during the scenario study period.
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