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Inter-technology Effects in Intelligent Transportation Systems

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Abstract

This project examines the expected benefits of varying combinations of ITS applications: Freeway Service Patrol, Changeable Message Signs, and Ramp Metering. The research analyzes the simulated results of a stylized network in a microscopic traffic simulator. The traffic network includes parallel roadways, ramp meters and changeable message signs. We have tested these technologies in various combinations. We measure effectiveness and define a measure of inter-technology economies. In brief, it is found that additional technologies are sub-additive, and more benefits come from each technology in isolation than when it is bundled with other technologies.

Keywords: Transportation System Management, Inter-technology Economies, Freeway Service Patrol, Changeable Message Signs, Ramp Metering, Intelligent Transportation Systems, Evaluation
Introduction

There has been recent interest in understanding the economic viability of Intelligent Transportation Systems (ITS) technologies, such as route guidance, freeway service patrols, traveler information and traffic control, to determine their ability to substitute for physical infrastructure investment. Incident management programs are one of the key elements of ITS. The goal of such programs is to clear incidents and return traffic flow on the roadway to normal as soon as possible. Incident management programs have been introduced in many places to help reduce the time to detect and the duration of incidents. They make use of ITS services and coordinate among the various operating agencies to meet the goals of reduction in the detection and clearance of incidents.

Highway assistance services, also called freeway service patrols (FSPs), are one of the main approaches used by incident management programs. These services use vehicles to patrol heavily traveled segments and congested sections of freeways that are prone to incidents (Freeway Operations Section 2000). The main goals of the Freeway Service Patrols are to help identify incident locations, reduce the duration of incidents, restore full freeway capacity, and diminish the risks of secondary accidents to the motorists (Fenno and Ogden 1998). The role of the patrols is to clear the majority of incidents without any assistance from other agencies. In case of major incidents, the patrols help assess the equipment and manpower needed to clear the incidents, coordinate with the other agencies involved, provide the needed traffic control and act as a buffer between the workers and traffic. They also help detect and verify incidents like major accidents and pass on the required information to the transportation management centers (TMCs).

Changeable Message Signs (CMS) (also called Variable Message Signs) give information and recommendations to drivers, making them aware of upcoming traffic conditions along their trip. These dynamic messages inform drivers about unexpected incidents and congestion and suggest alternative routes so that delay is minimized.

Ramp metering programs (RMP), aimed primarily at recurring congestion, have been applied in numerous cities in the United States as well as throughout the world. Ramp metering aims to limit the number of vehicles entering the freeway from entrance ramps at specific periods of time so that freeway flow can be maintained at a desired service level. Excess demand is forced to wait at the entrance ramp. The intention of ramp metering is, therefore, to maintain uninterrupted, non-congested flow on the freeway as long as possible by transferring delay from the freeway to the entrance ramp. The diversion of traffic to alternative routes in the corridor, less congested departure times or even different modes of transportation is an anticipated consequence of ramp metering.

This project aims to evaluate the benefits associated with various combinations of these three ITS applications (FSP, CMS, and RMP). The results obtained from each case are analyzed and the optimal use of ITS technologies has been determined. The methodology adopted is described in the form of a flowchart (Figure 1).

This paper begins with a brief description of the methodology used for traffic simulation. The assumptions and details regarding the traffic network are described in the
next section. The subsequent sections delve into modeling the traffic network and describing our measure of effectiveness. A summary of study results and conclusions are then provided.

**Input Characteristics and Assumptions**

The input flow characteristics of the system are shown in Figure 2. The free flow speed of vehicles is taken as 88 km/hr on freeways and 60 km/hr on entrance ramps. The flow distribution is assumed to be uniform with traffic comprising all cars. The initial warm up time for the simulation is set at 15 minutes for an overall 120 minutes of the simulation run. The input traffic demand consists of three states 1, 2 and 3. The states 1 and 3 correspond to base flow rates of 8000 vehicles / hour, while state 2 carries a flow of 10,000 vehicles / hour in the entrance section. All the ramps allow 600 vehicles / hour into the freeway for all the three states. State 1 lasts from 0 to 45 minutes, state 2 from 45 to 75 minutes and state 3 from 75 to 120 minutes as shown Figure 2. The traffic incidents are activated after 30 minutes of simulation run at a specific fixed location with varying rates of clearance. Optimal ramp metering rates were determined from initial simulations. However, it is assumed that the optimal ramp metering rates remain unaltered even during incidents in the downstream of the ramp meters.

The network includes parallel roadways, ramp meters and changeable message signs. We analyzed multiple or group ramp meters. Figure 3 illustrates the test scenario. A downstream bottleneck on a freeway has two upstream ramp meters with a CMS at the diverge point where the freeway with three lanes splits into two freeway sections each of two lanes. The location of the incident is after the second ramp downstream bottleneck as illustrated in the Figure 3.

The four ramps are tested under both metered and unmetered scenarios. To maintain simplicity for analysis, we restrict ourselves to one type of meter control. We employ Changeable Message Signs for some scenarios. We specify the proportion of traffic that receives the message and the probability of acting on it at the traffic intersection. The evaluation is made for different proportions of people receiving and acting on the message and see how savings change as a result of these different proportions. We assume that CMS informs 100% of drivers, but the percent who act based on the message varies from 0 to 100%. When analyzing CMS, we consider the optimal switching rate for that case. Using different actions, each corresponding to a specific CMS, the turning probability is altered. We believe that with an appropriate severity of message and some experience, turning probabilities can be tuned. FSP is not directly included in the simulator, but can be modeled by injecting an incident and accelerating the clearance rate. The blockage effects 1 or 2 lanes and the clearance rate of the incident can be changed.

**Modeling**

This research employs the AIMSUN2 (Advanced Interactive Microscopic Simulator for Urban and Non-urban networks) microscopic traffic simulator. AIMSUN2 continuously models the behavior of each vehicle in the network, using car following and lane changing models. The traffic links or sections in the traffic simulator are
represented in the form of channels of pipes for freeways and ramps. The simulator allows users to vary percentages of different vehicles like cars, trucks and buses. The input traffic demand is specified by the means of a result container, which comprises different states, varying traffic flow demands based on time of the day (morning, afternoon and evening). Ramp metering control is performed by loading a control plan, which contains the details about the traffic flow from the ramps onto the freeway (ramp metering rate). The modeling system allows adaptive, fixed and uncontrolled ramp metering with user defined minimum, initial and maximum flow metering values.

Changeable message signs (CMS), which dictate splitting percentages at junctions, can also be modeled directly in AIMSUN by inputting the percentage of drivers who will respond based on a given message. The optimal CMS splitting percentages for different scenarios is determined by compiling alternative splitting percentages between two paths at the CMS and then choosing the rate that maximizes the overall measure of effectiveness. Freeway service patrols (FSP) are simulated by generating a traffic incident in the network which gets cleared after a given time interval determined by the user to reflect the level of service of FSP. The simulator allows creating incidents on single or multiple lanes depending on the time when they are activated, duration (size) and location in a section of the network.

The ramp metering rate optimization process involves comparison of downstream bottleneck sections for each of two ramps by performing a number of simulations. Each simulation varies the traffic demands and metering rates for the ramps without any incident, and thus no need for CMS or FSP. The bottleneck sections were compared using basic traffic characteristics of flow, speed and density for each of the cases and the results of the analysis are shown in Table 1. The optimal case that corresponds to maximum flow is selected as metered flow rates for the ramps. These metered flows are entered as inputs for the next stage of the analysis. We selected test G (shown in bold in Table 1) because it resulted in more flow than all of its other counterparts, which is consistent with many ramp metering strategies. In the analysis shown in Table 1, section 12 denotes the downstream bottleneck section for first ramp meter while section 13 denotes the downstream bottleneck for second ramp meter. Due to complexity of the traffic simulation modeling and time constraints we used a constant optimal metering rate of 600 vehicles per hour for all scenarios. Such an assumption would lead to some under-estimating of positive impacts of using adaptive ramp metering instead of a constant metering rate. Once the optimal traffic demands with metering rates are determined, the final simulation runs are performed with the integration of CMS and FSP with (or without) optimal ramp metering rates. We designed on ramps long enough to allow the total inflow of vehicles entering the network during the simulation cycle at all times and thus accounted for different on ramp delays for different scenarios.

Measures of Effectiveness

Once the fixed ramp metering rates are obtained, these values are fed into the microscopic traffic simulator and the analysis is performed with different combinations of CMS turning flow percentages at the diverge point and with different incident durations. To determine the efficiency of our test traffic network, we measure the expected net benefits of some combination of ITS applications.
Inspired by the notion of consumer’s surplus, our approach defines a Measure of Effectiveness (MOE) as in equation (1), illustrated in Figure 4. Figure 4 depicts that with the increase in output flow $Q_s$ to $Q_i$, the travel time decreases from $T_s$ to $T_i$. The figure represents two sets of conditions, both with fixed demand $D$, one with $S_s$ and the other with supply $S_i$. The shaded block in the figure represents the change in benefit (DB) in vehicle hour units, which is approximated by equation (1), which sums up benefit on all links (including ramps) on the network.

$$\Delta B_{is} = \sum_{j=1}^{J} \frac{1}{2} \left( Q_{sj} + Q_{ij} \right) \left( T_{sj} - T_{ij} \right)$$  (1)

$T_{sj}$ and $Q_{sj}$ are the fixed section travel time and outflow characteristics corresponding to a standard base case (one or two lane incident blockage and an equal split of mainline traffic between the top and bottom roads) for both metering and non-metering tests on section ’j’. $T_{ij}$ and $Q_{ij}$ are the sectional travel and flow characteristics for a varying incident duration and turning flow percentages for each section ’j’. In the above equation, ’J’ represents the number of sections in the system. $B_{is}$ represents how much the system ‘i’ is better or worse off than system ‘s’ in terms of vehicle hours for all sections, both freeway and ramp sections are included in this analysis. While the loaded traffic onto each ramp is fixed, the traffic on each section is not, due to queuing and capacity restrictions associated with incidents.

**Inter-technology Economies**

The primary objective of the paper is to test whether inter-technology economies are present between FSP, CMS and RMP. Inter-technology economies exist whenever the benefits of all technologies together exceed the sum of benefits of each technology individually. In other words, inter-technology economies are present if the individual benefit of consuming the outputs jointly is greater than the sum of the benefit of consuming the products separately. Thus, if $A$, $B$ and $C$ are benefits in units of vehicle hours corresponding to FSP, CMS and RMP in isolation and $D$ represents over all benefits for consuming all the technologies simultaneously, then an inter-technology economy implies $A + B + C < D$, a case we call super-additive. Otherwise (if $A + B + C > D$) there is an inter-technology diseconomy, a case we call sub-additive. Using this definition we examine how the MOE changes when we add additional ITS technologies for different incident clearance intervals with one and two lane blockages.

**Results**

First we test the change in benefit in the presence of ramp metering. As noted before, the actual demand on ramps is set as 630 vehicles/hour, while the optimal metering flow rate is 600 vehicles / hour. Table 2 shows how the benefit changes with additional ITS technologies indicating whether the system has a particular ITS technology for one-lane and two-lane blockage. In the case with no CMS, a standard 50 % split between the two routes is assumed, and for the cases with no FSP, a standard incident clearance rate of 20 minutes is assumed. Similarly, in the cases with FSP and CMS, the MOE corresponding to 10 minutes incident clearance rate and optimal splitting rates are considered.
In this first case, the change in benefit (in vehicle hours) for each case in one and two lane blockage is measured with respect to a standard base case with an incident, but no early clearance (i.e. no FSP), no diversion (50-50%) and standard metering rate of 600 vehicles/hour. Table 2 shows the change in benefit for a system with various combinations of FSP, CMS, and RMP for one and two-lane incident blockage. Table 2 also shows the change in benefit for one lane blockage are lower than two lane blockage, showing that the traffic conditions are more severe and worse in the latter case.

In order to determine whether Freeway Service Patrols and Changeable Message Signs are super-additive or sub-additive, we have to compare the savings attained from each of them separately and together. In order words, we need to find whether:

\[
\text{Benefits}(FSP,0) + \text{Benefits}(0,CMS) \geq \text{Benefits}(FSP,CMS)
\]  \hspace{1cm} (2)

where,

- \(\text{Benefits}(FSP, 0)\) denotes benefits attained only due to FSP, which is the difference between Benefits(with FSP, without CMS) and Benefits(without FSP, without CMS)
- \(\text{Benefits}(0, CMS)\) denotes benefits attained only due to CMS, which is the difference between Benefits(with CMS, without FSP) and Benefits(without CMS, without FSP)
- \(\text{Benefits}(FSP, CMS)\) denotes benefits attained by both FSP and CMS together, which is the difference between Benefits(with CMS, with FSP) and Benefits(without FSP, without CMS)

Putting the values for savings in (2), we see from Table 3 that we get \([\text{Benefits}(FSP, 0) + \text{Benefits}(0, CMS)] > \text{Benefits}(FSP, CMS), (65+212=277 > 247)\) which demonstrates that the two technologies are sub-additive. Similarly, we can perform the analysis in the case of two-lane blockages with ramp metering. Table 4 summarizes the analysis of inter-technology economies with and without freeway service patrols, changeable message signs, and ramp metering for one and two-lane blockages. The results obtained are for a 20 minute incident that is cleared in 10 minutes if there is a Freeway Service Patrol operating. The change in benefit obtained for cases without each technology are lower than with that technology which suggests that all of these technologies have positive benefits in congested prone networks. Also, the results illustrate that the impact of technology is greater for two-lane blockages than one-lane blockages since the individual benefits from FSP and CMS are higher for the former case. The results show that for both one and two-lane blockages the ITS technologies are generally sub-additive, generating more benefits separately than together. For the one-lane blockage case, CMS and RMP are sub-additive but for two-lane blockage they are super-additive. This one case of super-additivity may be because there is more mainline congestion during a two-lane blockage.
Conclusions

This research identifies and develops a method for measuring the benefits associated with bundles of technologies. This novel analysis of what we call inter-technology economies provides insights into how recurring and non-recurring traffic congestion can be alleviated with ITS technologies. It suggests that most of the gains can be obtained from whatever technology is deployed first, and that successive gains from additional technologies are smaller than the first application. It is observed that all but one of the cases we modeled demonstrated sub-additive benefits. This does not mean that multiple ITS technologies should not be pursued, but that the benefit claims of ITS when measured separately must not simply be added together. The more severe the incident, the more useful the ITS technology, either separate or together. For non-recurring congestion, Freeway Service Patrols are found to generate significantly more gains than either Changeable Message Sign or Ramp Metering applications. While many of the benefits may be sub-additive, there may be cost savings associated with deploying multiple technologies that should also be considered in any complete evaluation.

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REFERENCES


FIGURE 1: TRAFFIC SIMULATION METHODOLOGY

1. Create a traffic network using TEDI editor
2. Define characteristics for different sections of the network
3. Generate initial traffic flows for vehicle classes in Result Container
4. Create Ramp Metering module in control plan
5. Create CMS at an intersection
6. Save the network and load it in AIMSUN2
7. Load the traffic, control plan and create actions for each CMS
8. Create incident in a location with duration
9. Load the CMS, Incidents and Ramp Metering. Run Simulation and Save Results
Figure 2: Flow Characteristic Diagram

The diagram illustrates the flow characteristics over time, with the following key elements:

- **Q**: Vehicles per Hour
- **Simulation Time (Minutes)**
- **Mainline Flow (Flow for 3 lanes/hr)**
- **Ramp Flow (Flow for 1 lane/hr)**
- **Incident Injected Time**

The states 1, 2, and 3 are denoted as follows:

- **1**, **2**, **3**: Denote states 1, 2, and 3 respectively.
Figure 3: Test Network

CMS

Denotes Ramp

Direction of Traffic Flow

3 lanes

2 lanes

1 lane Ramps

End of section

Section 12

Incident

Section 13

1 lane Ramps

3 lanes

Direction of Traffic Flow
Figure 4: Benefit Measurement
TABLES

TABLE 1: Sectional Characteristics of Traffic Flow for Sections 12 and 13 By Varying Ramp Metering Flow

<table>
<thead>
<tr>
<th>Case Ramp Flow</th>
<th>SYSTE M veh/hr Total Flow</th>
<th>veh/hr Average Speed</th>
<th>veh/km</th>
<th>km/hr Total Flow</th>
<th>Average Speed</th>
<th>veh/km</th>
<th>km/hr Total Flow</th>
<th>Average Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 0</td>
<td>5823</td>
<td>21.13</td>
<td>59.38</td>
<td>2980</td>
<td>16.59</td>
<td>79.50</td>
<td>2976</td>
<td>14.35</td>
</tr>
<tr>
<td>B 100</td>
<td>6208</td>
<td>22.93</td>
<td>59.22</td>
<td>3075</td>
<td>17.83</td>
<td>77.73</td>
<td>3171</td>
<td>16.78</td>
</tr>
<tr>
<td>C 200</td>
<td>6613</td>
<td>24.92</td>
<td>58.90</td>
<td>3195</td>
<td>19.57</td>
<td>75.00</td>
<td>3402</td>
<td>19.95</td>
</tr>
<tr>
<td>D 300</td>
<td>7000</td>
<td>26.91</td>
<td>58.42</td>
<td>3287</td>
<td>21.13</td>
<td>72.10</td>
<td>3576</td>
<td>22.18</td>
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<tr>
<td>E 400</td>
<td>7373</td>
<td>28.89</td>
<td>57.78</td>
<td>3342</td>
<td>22.99</td>
<td>68.56</td>
<td>3727</td>
<td>24.54</td>
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<tr>
<td>F 500</td>
<td>7725</td>
<td>33.43</td>
<td>54.07</td>
<td>3445</td>
<td>36.16</td>
<td>52.14</td>
<td>3946</td>
<td>30.38</td>
</tr>
<tr>
<td>G 600</td>
<td>7978</td>
<td>44.74</td>
<td>44.58</td>
<td>3423</td>
<td>49.96</td>
<td>39.91</td>
<td>4021</td>
<td>33.74</td>
</tr>
<tr>
<td>H 700</td>
<td>7923</td>
<td>47.53</td>
<td>42.81</td>
<td>3356</td>
<td>52.38</td>
<td>38.30</td>
<td>3976</td>
<td>35.29</td>
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<tr>
<td>I 800</td>
<td>7911</td>
<td>49.83</td>
<td>42.00</td>
<td>3341</td>
<td>53.13</td>
<td>38.46</td>
<td>3982</td>
<td>34.73</td>
</tr>
</tbody>
</table>

TABLE 2: Summary Results From Simulation Runs

<table>
<thead>
<tr>
<th>Blockage: 1 Lane</th>
<th>2 Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases</td>
<td>With Metering</td>
</tr>
<tr>
<td>1 No FSP, No CMS</td>
<td>284</td>
</tr>
<tr>
<td>2 FSP, No CMS</td>
<td>348</td>
</tr>
<tr>
<td>3 No FSP, CMS</td>
<td>496</td>
</tr>
<tr>
<td>4 FSP, CMS</td>
<td>531</td>
</tr>
</tbody>
</table>

Note: Change in benefit in vehicle hours

TABLE 3: Illustrative Inter-technology Economy Matrix (FSP, CMS, RMP) for 1 Lane Blockage

<table>
<thead>
<tr>
<th>With CMS</th>
<th>Without CMS</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>With FSP</td>
<td>531</td>
<td>348</td>
</tr>
<tr>
<td>Without FSP</td>
<td>496</td>
<td>284</td>
</tr>
<tr>
<td>Savings</td>
<td>35</td>
<td>64</td>
</tr>
</tbody>
</table>

\[ 212 + 64 = 276 \] \[ > \] \[ 247 = 531 - (284) \]

Note: Change in benefit in vehicle hours compared to baseline case of no ramp metering with one lane blockage.
TABLE 4: Inter-technology economy (FSP, CMS, RMP) For One and Two Lane Blockage

<table>
<thead>
<tr>
<th>Technologies</th>
<th>1 Lane Blockage</th>
<th>2 Lane Blockage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS Result</td>
<td>CS Result</td>
</tr>
<tr>
<td>FSP,0,RMP</td>
<td>Sub-additive</td>
<td>Sub-additive</td>
</tr>
<tr>
<td>Benefits(FSP,0,0)</td>
<td>140</td>
<td>402</td>
</tr>
<tr>
<td>Benefits(0,0,RMP)</td>
<td>284</td>
<td>523</td>
</tr>
<tr>
<td>Benefits(FSP,0,RMP)</td>
<td>348</td>
<td>568</td>
</tr>
<tr>
<td>0,CMS,RMP</td>
<td>Sub-additive</td>
<td>Super-additive</td>
</tr>
<tr>
<td>Benefits(0,CMS,0)</td>
<td>242</td>
<td>129</td>
</tr>
<tr>
<td>Benefits(0,0,RMP)</td>
<td>284</td>
<td>523</td>
</tr>
<tr>
<td>Benefits(0,CMS,RMP)</td>
<td>496</td>
<td>716</td>
</tr>
<tr>
<td>FSP,CMS,0</td>
<td>Sub-additive</td>
<td>Sub-additive</td>
</tr>
<tr>
<td>Benefits(FSP,CMS,0)</td>
<td>141</td>
<td>401</td>
</tr>
<tr>
<td>Benefits(0,CMS,0)</td>
<td>242</td>
<td>128</td>
</tr>
<tr>
<td>Benefits(FSP,CMS,0)</td>
<td>257</td>
<td>484</td>
</tr>
<tr>
<td>FSP,CMS,RMP</td>
<td>Sub-additive</td>
<td>Sub-additive</td>
</tr>
<tr>
<td>Benefits(FSP,CMS,RMP)</td>
<td>257</td>
<td>485</td>
</tr>
<tr>
<td>Benefits(0,0,RMP)</td>
<td>284</td>
<td>523</td>
</tr>
<tr>
<td>Benefits(FSP,CMS,RMP)</td>
<td>531</td>
<td>734</td>
</tr>
<tr>
<td>(baseline: metering off)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSP,CMS,RMP</td>
<td>Sub-additive</td>
<td>Sub-additive</td>
</tr>
<tr>
<td>Benefits(FSP,0,RMP)</td>
<td>64</td>
<td>45</td>
</tr>
<tr>
<td>Benefits(0,CMS,RMP)</td>
<td>212</td>
<td>148</td>
</tr>
<tr>
<td>Benefits(FSP,CMS,RMP)</td>
<td>247</td>
<td>166</td>
</tr>
<tr>
<td>(baseline: metering on)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Change in Benefit in Vehicle Hours. All cases except last assume baseline with all technologies off (0,0,0) with one or two lane blockage respectively. Final case assumes baseline with metering on (0,0,1) Benefits are calculated from Table 2. Incidents 20 minutes without FSP, 10 minutes with FSP.