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Framework for Evaluation of Communication System Loading for ATIS and ATMS Applications

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ABSTRACT

Significant efforts are being made at present to define, evaluate, and ultimately deploy, various forms of Intelligent Transportation Systems (ITS). These systems permit the implementation of advanced traffic control strategies through the application of advanced surveillance, control and communication systems. Traditionally, the evaluation of the performance of these communication systems and traffic networks has been performed predominantly independent of each other.

This paper describes the development and application of an extension to an ITS benefits evaluation model to permit a partially coupled evaluation of the communication system loading and the ATMS/ATIS functions. This extended model is capable of estimating dynamic local and network wide communication loadings that depend on the spatial and temporal traffic demands, the network topology, the characteristics of the communication hardware and the communication system operating rules.

The model is applied in this paper to a simple hypothetical network to demonstrate the potential benefits of carrying out a partially coupled evaluation of communication system loading and traffic network efficiency. A sensitivity analysis was carried out to determine the impact of the fraction of ITS equipped vehicles and the level of congestion on the level of communication loadings. It was demonstrated that, as a result of congestion and traffic diversion, antenna communication loads did not uniformly increase in direct proportion to the average number of equipped vehicles entering the network.

I. INTRODUCTION

During the past decade, much interest has been generated by the potential benefits that may be obtained from the application of advanced technologies to the operation and management of transportation systems. Recently, technological advances in computer and communications hardware have permitted the field operational testing of several Intelligent Transportation Systems (ITS) including the PathFinder system in Los Angeles, California, the TravTek system in Orlando, Florida, and the Metropolitan Model Deployment Initiative (MMDI) in San Antonio, Phoenix, and Seattle. In the U.S., an effort is currently underway to define a nation-wide open ITS architecture framework, which would, in conjunction with the adoption of appropriate communication protocol standards, facilitate the wide-scale deployment of compatible ITS services nation wide. It is expected that once this architecture is fully defined, private consortia would produce market value-added systems to operate within this architecture. The evaluation of this architectural framework, and any systems that are to operate within this framework, must include an assessment of (i) the communication system loadings that are part of the Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS), and (ii) the efficiency of the traffic network.

Historically, the evaluation of the loading and performance of the communication system and the efficiency of the traffic network has been largely uncoupled. However, there exists an interdependence between the performance of the communication system and the traffic network. These interaction effects which may cause a degradation in performance of both sub-systems, are typically very complex and thus difficult to solve analytically.

This paper attempts to study the effect of coupling the evaluation of communication system loading and ATIS/ATMS efficiency. First, the basic elements required to model an ITS communication system are described. Second, the nature of the

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interdependence between the evaluation of communication systems and ATIS/ATMS is examined. Third, the development and application of an extension to a standard ITS benefits modeling approach, called INTEGRATION, is described. This model can be utilized to develop estimates of the dynamic local and network wide communication loadings, where these time varying loads are determined as a function of the variation in traffic demands, the network topology, the characteristics of the communication hardware and the communication system operating rules.

The range of analyses possible using this unified simulation approach is illustrated by means of a sample application of the model to a simple hypothetical network. Lastly, conclusions and recommendations are made on the basis of the work carried out thus far.

II. Communication System Building Blocks

In order to permit the modeling of a communication system, four distinct entities need to be identified, namely: (i) information customers/providers, (ii) information communication channels and/or transceivers, (iii) information processors, and (iv) information message protocols. This section describes these communication system building blocks in some detail before describing, in the subsequent sections, the specific communication system modeling features that were incorporated to-date in the INTEGRATION model. It is anticipated that, following a period of field testing these initial coupled capabilities, these capabilities will need to be further enhanced to better meet users' long term analysis needs.

A. Information Customers/Providers

The information customers/providers are primarily the vehicles traveling through the network. These customers are described in the model in terms of how much information they need and how much they can provide, and when such information requesting or providing is likely to occur.

Behavioral rules describing information requesting may vary significantly in complexity. For example, vehicles may operate under a very simple information request rule whereby the vehicles make information requests at a fixed time frequency, say every five minutes, or at a fixed distance interval, say every five kilometres. Information request rules may also be much more complex, where the decision to request information is a function of network location, the level of traffic congestion encountered, and the trip purpose. For example, a vehicle could request a route at the start of its trip, and subsequently request en-route routing updates every 15 minutes or 20 km, unless traffic congestion is encountered, at which time the frequency of its routing update requests increase to once every 5 minutes or 5 km.

Behavioral rules also govern the provision of information by vehicles that act as probes. For example, an information provision rule might state that vehicles will provide probe information every 5 minutes, unless they encounter traffic congestion, at which time the reporting frequency may increase to the transmission of a new probe report at the conclusion of the traversal of every single link.

The above behavioral rules only serve as an example of the range of rules that could be adopted within an ATIS/ATMS. Clearly, the specific behavioral rules are a function of the type of ATIS capabilities of the vehicle (centralized or decentralized), and the communication capabilities of the vehicles involved (cellular based wireless link, short-range beacon transmissions, etc.). The above analysis becomes especially interesting when a given system architecture or vehicle configuration supports multiple communication media, as it is likely to be the case in the future.

B. Communication Channels

The information communication channels/transceivers represent the various media that can be utilized to carry the information requested by the data customers and provided by the data providers. These media are primarily described in terms of the number of available channels and the information carrying capacity per channel. Associated with the transceivers is also an indication of the effective range, where this range may vary considerably. For example, loop detectors or transponders may only be able to communicate with a vehicle when it is in a very specific network point location. Local highway advisory radio (HAR) may be able to communicate directly with all vehicles on a particular link segment, whereas a cellular system may be able to communicate with all the vehicles within a specific region. Finally, other systems, such as an FM sub-carrier, may be able to broadcast to all the vehicles in the entire area that is to be simulated. In addition, some of the communication channels/transceivers are two-way, while others are strictly one-way.

C. Information Processors

Information processors represent the basic units that process, translate, and package the information. These processors may be concentrated at a single centralized Traffic Management Center (TMC), be distributed through a number of sub-area TMCs, or be fully decentralized at each road-side location. In each case, some in-vehicle computation will likely be required, but the extent of the need will likely vary considerably. The estimation of computational load becomes especially challenging when this loading is dynamic and adaptive. The information processor characteristics, that are of primary interest, are the number of available CPUs and the processing speed per CPU.

D. Information Message Set Protocol

The final element of the communication system is the message set protocol. This protocol defines the set of information types that will be permitted to be communicated throughout the various communication subsystems. The protocol defines the message purpose, size and format for each media type. For example, the literature indicates a typical travel request message to consist of several fields, namely: the message type, origin, destination, transit type, travel time and time stamp [1]. This message would result in a total message size of 208 bits (26 bytes) as follows: 6 bits for the message type, 64 bits for the origin identification, 64 bits for the destination identification, 6 bits for the transit type, 32 bits for the travel time estimate, and 32 bits for the time stamp [1]. In addition to providing insights into the transmission overhead, the message structure also conveys functionality.

Within the above building block scheme, information customers would be connected by means of various communication channels/transceivers to the information processors. In addition, some information processors may be linked to each other by means of additional communication channels/transceivers, as would be the case in a distributed TMC configuration. Furthermore, in an automated highway system (AHS) scenario, communication channels may be utilized to directly link various vehicles to each other, as well as to the roadside TMC slave.

III. Interdependence of Evaluation

There exists several levels at which the interdependence between the evaluation of ATIS/ATMS efficiency and the communication system loading can be considered, as indicated below.

A. Independent Assessments

At one extreme, the evaluation of the communication system and traffic network can be conducted completely independent of each other. An independent evaluation implies that within the traffic analysis, assumptions must be made regarding the ability of the communication system to receive probe and other information, to process the data, and to re-transmit it to information customers in a reliable and timely manner. Typically, it is therefore assumed that the communication system is able to receive all data provided by data providers (probes), process it with a fixed lag time (often assumed to be zero) and provide these data back to all data customers. Essentially, this assumption implies that no capacity bottleneck exists in the communication system. Conversely, an independent communication system evaluation implies that assumptions are made regarding the loads placed on the communication system by the vehicular traffic. Since the communication load estimation analysis is performed independent of the traffic analysis, the traffic loadings are usually approximated. Surrogate indicators might be derived by utilizing link length and average link density to compute the maximum possible vehicle loads. However these indicators are usually insensitive to the dynamic traffic performance.

Both methods of independent analysis fail to capture much of the interdependency of each of the subsystems. The performance of the communication system in providing information to drivers impacts these drivers' ability to make sound routing decisions. In turns, these routing choices cause an increase or decrease in the level of congestion on various parts of the network, and the resulting level of congestion directly impacts the communication loadings.

B. Approaches to Coupling

A first step, to coupling the communication and ATIS evaluation, can be achieved by reducing the need for assumed inputs to one of these evaluations by performing the traffic and communications analyses in series. For example, instead of estimating communication system loadings on the basis of maximum possible vehicle loadings, it would be possible to input communication loadings directly from modeled traffic loading patterns. This could be accomplished in two ways.

First, traffic network measures of performance (MOP) such as average link flow and density, could be estimated from the traffic network evaluation. Subsequently, communication loadings could be estimated from these traffic MOPs during an intermediate step and provided as inputs to the communication system evaluation. A more direct method is to directly estimate the communication system loadings within the traffic analysis. This would permit complex information requests and provision rules to be accurately reflected directly in the estimated communication loadings.

Complete coupling further requires that the modeled behavior of the traffic be made a function of the performance of the communication system. This requires that the communication system capacities, as well as operating characteristics, be considered in the traffic evaluation in parallel or concurrent, rather than serial or sequential fashion. For example, if a severe incident causes considerable congestion, the number of information re-routing requests received at the local cellular station may increase to such a level that not all requests can be served. Consequently, some vehicles would be denied re-routing information, and would be unable to re-route. This could cause them to incur additional delays beyond those which an unconstrained traffic routing analysis would have considered.

A fully coupled evaluation would therefore permit a quantitative assessment of the potential limiting impact that communication system characteristics would have on traffic performance. In addition, a fully coupled evaluation could also assess the potential impacts of traffic characteristics on the performance of the communication system.

IV. A PARTIALLY COUPLED EVALUATION TOOL

The ITS traffic simulation model, called INTEGRATION, has been extended to permit a partially coupled evaluation of communication system loading and ATIS/ATMS. INTEGRATION is a microscopic traffic simulation model that represents individual vehicles as distinct entities [2,3,4]. The model explicitly represents traffic control devices such as traffic signals, ramp meters, and variable message signs. The model also permits up to five different driver classes to be represented, where each driver class is distinguished by its routing characteristics, ability to make requests for re-routing information and ability to provide vehicle probe data. The INTEGRATION model was used in the FHWA ITS National Architecture Study [5], and has been successfully used to model many existing traffic networks, including networks for Orlando, Florida [6,7], Salt Lake City, UT [8], Phoenix, AZ [9], and San Antonio, TX [10].

The INTEGRATION model was enhanced as part of this first effort, to incorporate the fundamental functional capabilities required to develop dynamic local and network-wide communication loadings. These initial capabilities enable a partially coupled evaluation of ATIS/ATMS and communication systems to be conducted as the model directly outputs communication loads. A fully coupled evaluation, which is being implemented, will explicitly consider communication system constraints on the ability of vehicles to successfully transmit/receive information.

Table 1 provides the specific communication system characteristics that are represented within the model, along with the objective measures provided by the model representing the operating characteristics of the communication sub-system and traffic network. As indicated in Table 1, the user specifies the x-y coordinates of each antenna, as well as its effective coverage range and channel bandwidth. The INTEGRATION model subsequently outputs both communication loadings by antenna and traffic network MOPs for each vehicle, origin-destination pair, vehicle class, and link [11,12,13, and 14].

TABLE 1: COMMUNICATION SYSTEM CHARACTERISTICS

Communication Inputs	Communication Outputs	Traffic Model Outputs
Antenna x and y coordinates (km)	Number of calls to each antenna	Average trip duration (s)
Data bandwidth (bits)	Total demand (bytes) to each antenna	Average trip length (km)
Antenna range (km)		Average number of vehicle stops (stops)
Transmission frequency (Mhz)		Average fuel consumption (l)
Message size at start of trip (bits)		Average emissions (g) (HC, CO, CO_2, NO_x, and PM)
Message size during trip (bits)		Average accident risk (crashes per million vehicle kilometers traveled)

V. SAMPLE MODEL APPLICATION

This section describes the application of the INTEGRATION model to a simple hypothetical network. This sample application is intended to illustrate the potential of carrying out a partially coupled evaluation of communication systems and traffic networks, and is not to make conclusions regarding a specific communication system's characteristics. Instead, the sample results are examined to illustrate the model capabilities and to determine whether a partially coupled analysis permits insights of a type not possible in a less coupled analysis.

A. Study Description

Traffic Network Characteristics As illustrated in Fig. 1, the hypothetical network consists of a freeway section (links 1 through 10) and a parallel arterial roadway (links 11 through 14). The main characteristics of the freeway and arterial links are provided in Table 2. The freeway section consists of three lanes in each direction except for a two-lane bottleneck located at link 6.

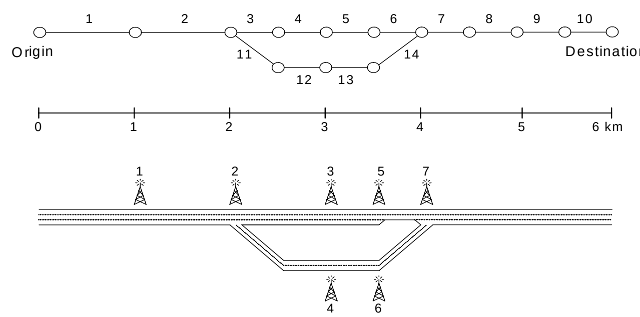

FIG. 1: LAYOUT OF STUDY NETWORK

TABLE 2: SUMMARY OF LINK CHARACTERISTICS

Link Description	Saturation Flow (vph)	Free-speed (km/h)	Speed-at-Capacity (km/h)	Jam Density (veh/km/lane)
Freeway	2100	100	80	150
Arterial	1800	80	65	150

Traffic Demand Characteristics A time varying mean traffic demand was loaded on the network, as illustrated in Fig. 2. The mean traffic demand increased in 5-minute increments to a maximum of 5,000 veh/h after 20 minutes of simulation, and subsequently remained at this level for 30 minutes, before reducing to zero after 70 minutes of simulation. The simulation duration was extended for an additional 20 minutes in order to clear the network of any en-route vehicles. It should be noted that the vehicle departures were random within each 5-minute interval considering a Poisson distribution of departure rates (vehicle time headways followed a shifted negative exponential distribution). It should be noted, however, that the random number seed was held constant for all the scenarios in order to ensure consistency across the various simulation runs without the need for multiple repetitions.

Two ATIS driver classes were modeled. Class 1 drivers did not have the ability to request routing information. As a result, all ATIS class 1 drivers utilized the freeway route, regardless of the level of congestion. ATIS class 2 drivers had the ability to request re-routing information, providing them with the opportunity to use the parallel arterial route. The proportion of equipped vehicles (driver class 2) was held constant during the entire course of a given simulation run, but was varied across the different scenarios. Vehicles were assigned to each class randomly based on a uniform distribution.

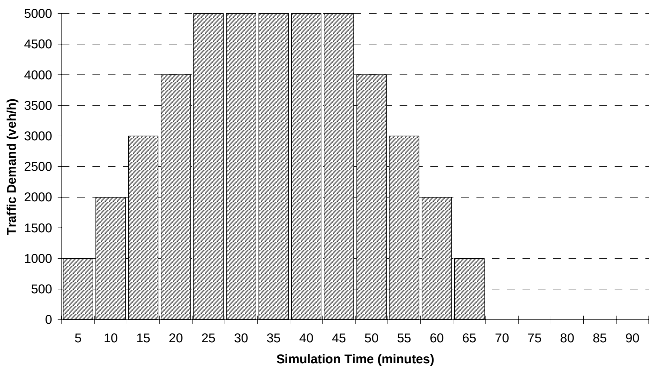

FIG. 2: TIME SERIES OF TRAFFIC DEMANDS

The speeds of vehicles entering and traveling along the network were computed based on the Van Aerde car-following relationship which is calibrated using the four link parameters that are listed in Table 1. A more detailed description of the car-following model can be found in the literature [4]; however it is sufficient to note that the model considers a steady-state car-following relationship of the form illustrated in Fig. 3 where the vehicle speed depends on the distance headway between it and its preceding vehicle in the same lane.

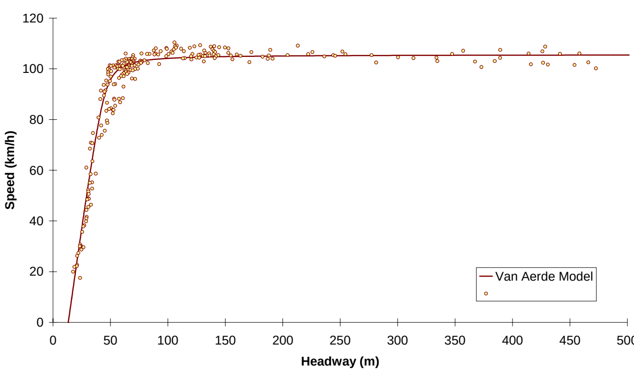

FIG. 3: SAMPLE CAR-FOLLOWING RELATIONSHIP FOR FREEWAY ROADWAYS

Communication System Characteristics As illustrated in Fig. 1, seven antennae were also modeled to exist within the network. Each antenna was initially modeled to have an infinite range and bandwidth capacity. In addition, a simple information request behavior rule was adopted, stating that equipped vehicles request route information at the start of their trip and at a fixed 60-second time interval thereafter. The initial travel request message was set to be 26 bytes long while the en-route messages were set to be 64 bytes [1]. Vehicles made requests to the nearest antenna to their x-y position as they traveled along the network.

B. Sample Model Results

The impact of two factors on communication loadings was considered; level of market penetration (LMP) of equipped vehicles, and level of congestion. The LMP was changed in the demand input data, while the level of congestion was varied by introducing an incident to the freeway segment.

Impact of Level of Market Penetration Fig. 4 illustrates the number of calls received by antenna 2 as a function of the simulation time for three typical LMPs. As expected, Fig. 4 verifies that, in some parts of the network, the number of calls generally increases with the number of equipped vehicles on the network. This increase in number of equipped vehicles occurs either when the traffic demand increases or when the LMP increases. Thus, for the 10%, 20% and 50% LMP curves, it can be observed, that there is an increase in the number of calls from time 20 minutes to 50 minutes into the simulation as a result of the increase in the traffic demand. In addition, the total number of calls appears to increase approximately linearly as a function of LMP.

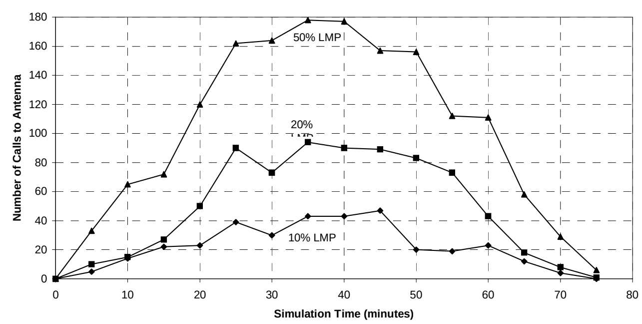

FIG. 4: IMPACT OF LEVEL OF MARKET PENETRATION ON NUMBER OF CALLS TO ANTENNA 2 (CALLS/5-MINUTES)

Fig. 5 illustrates the number of calls received at a different network location, namely at antenna 5. In this case, the number of calls does not increase in proportion to the increase in LMP. While all vehicles must travel through the portion of the network that is within the range of antenna 2, antenna 5 is located along the freeway section for which an alternative parallel arterial route exists. Consequently, vehicles diverting from the freeway travel along the arterial and do not make calls to antenna 5. As a result, for an LMP of 10%, there is a considerable amount of congestion near antenna 5, which causes the relatively small number of equipped vehicles to make a large number of calls per vehicle. When the LMP is 20%, more equipped vehicles remain on the freeway, but the significantly reduced level of congestion considerably reduces the number of calls per vehicle. Finally, at an LMP of 50%, many equipped vehicles remain on the freeway and pass by antenna 5. Fig. 5 clearly demonstrates that the computation of antenna loadings can be a very complex function of numerous factors.

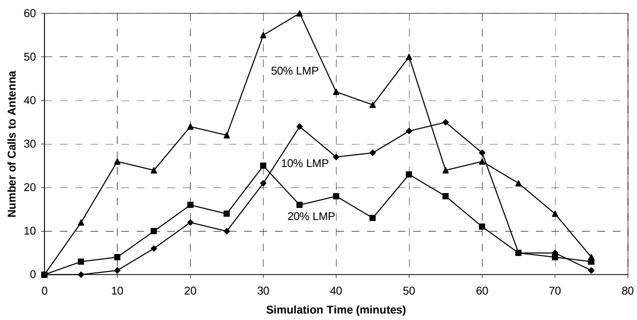

FIG. 5: IMPACT OF LEVEL OF MARKET PENETRATION ON NUMBER OF CALLS TO ANTENNA 5 (CALLS/5-MINUTES)

Consider Fig. 6, which illustrates the proportion of the total number of calls made during the simulation, associated with each antenna. When no diversion effect is present (antennae 2 & 7), it might be expected that the proportion of calls received remains constant. Fig. 6 illustrates that this is not the case, particularly for LMP less than 40%. These variations are caused by congestion, as vehicles which travel more slowly as a result of congestion, are within range of a particular antenna for a longer period of time. Therefore they make more calls to that antenna than they would if they had been traveling in a less congested mode.

Fig. 6 also illustrates that, as the LMP increases, the number of vehicles that divert increases and thus the number of calls received by antenna 6 also increases.

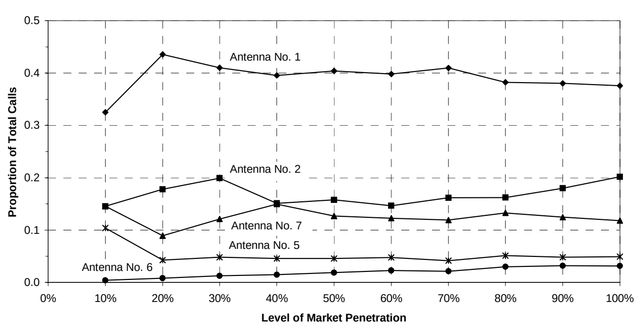

FIG. 6: IMPACT OF LEVEL OF MARKET PENETRATION ON THE PROPORTION OF ANTENNA CALLS

Impact of Non-Recurring Congestion Fig. 7 illustrates the number of calls received by antenna 3 as a function of the simulation time and the level of non-recurring congestion imparted by an incident at the end of link 5. The incident blocks 1½ lanes, which corresponds to a 50% reduction in the link's capacity. In each case, the incident blockage starts at time 25 minutes and has a duration ranging from 10 to 30 min. As indicated in Fig. 7, the occurrence of the incident results in more than a four-fold increase in the number of calls received by antenna 3. The figure also illustrates that for a longer incident duration, communication loading remains at an elevated level for a longer period of time.

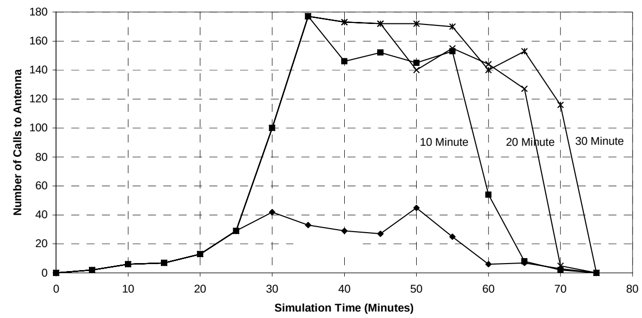

FIG. 7: IMPACT OF INCIDENT DURATION ON NUMBER OF CALLS TO ANTENNA 3 (CALLS/5-MINUTES)

VI. CONCLUSIONS

Currently, communication systems and ATIS/ATMS evaluations are carried out in a predominantly uncoupled fashion. However, there exist interdependencies between the communication system and ATIS/ATMS efficiency evaluations. The potential negative impact, on the accuracy of the evaluation, of omitting these interdependencies within an overall ITS evaluation, has generally not been quantified.

Current activities indicate that future ATIS/ATMS systems will rely even more heavily on communication systems in which complex behavior rules will be used to determine the frequency of information requests and provisions, and the size of these information packages. The INTEGRATION model has therefore been extended to permit partially coupled evaluations of communication systems and ATIS/ATMS to be conducted. This paper describes the framework for this coupling and how it considers the flow of information from the traffic flow sub-system to the communication loading sub-system, while a future paper will describe the impact of a further feed back loop from the communications module to the traffic model.

The limited results, which were presented in this paper, have indicated that an increase in the number of ITS equipped vehicles in a network does not necessarily result in a proportional increase in the antenna communication loads. Furthermore, increases in traffic congestion produce significant differential increases in the loads at some antennae. These results clearly show that estimating the communication loads is not a simple multiplicative process and requires a sophisticated approach that explicitly considers coupling effects.

The INTEGRATION model provides a unique framework to conduct a partially coupled evaluation of a larger communication system and traffic network.

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